MACHINE CASTING OF FERROUS ALLOYS

INTERIM TECHNICAL REPORT

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by

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ABSTRACT

This report describes research conducted at Massachusetts Institute of Technology during the first half of the second year of a joint university-industry research program on casting of ferrous alloys. Work during this period continued on both low temperature "model" systems, and on a ferrous alloy. Emphasis was on casting of semi-solid alloys, especially semi-solid alloys produced in a continuous slurry producer.

A low temperature casting system described earlier was improved. This system consists of a continuous semi-solid slurry producer, "gel" chamber, and casting machine. The system was used to produce about one hundred castings of Sn-15%Pb alloy. High speed motion pictures taken through a transparent die show that the semi-solid slurry flows into the die more smoothly than fully liquid metal, entrapping less gas. Radiography and metallography show the semi-solid castings are freer of entrapped gas and shrinkage than are castings made similarly of fully liquid metal.

Construction and testing of a casting system for high temperature alloys was completed. The system comprises a continuous slurry producer described earlier, a "gel" chamber, and a "low pressure" die casting machine. The completed casting system was tested using copper base 905 alloy (88wt%Cu, 10wt%Sn, 2wt%Zn) as a model high temperature alloy system. Radiographic analysis of 51 castings made show that overall casting quality improves with increasing fraction solid in the slurry.

Modifications of the high temperature casting system described above were made to permit casting ferrous alloys. Successful preliminary experiments were carried out with a hypoeutectic Fe-2.5%C-3.1%Si cast iron alloy.

Work was continued to develop design parameters for an electromagnetic piston for rapid mold injection of semi-solid metals. The electromagnetic casting machine described earlier was modified. Modifications include an improved coil-die arrangement and development of a multiple discharge triggering system. Castings produced with a semi-solid aluminum alloy using the modified machine show improved die filling and reduced air entrapment.

A computer heat flow analysis was developed to describe effects of casting and die conditions, and materials on die thermal behavior. Effects of fraction solid (for Rheocast and Thixocast metal) and effect of superheat (for fully liquid metal) on die thermal behavior were examined. Preliminary results indicate that both die surface temperature and temperature gradient are lowered significantly when a cast iron alloy is cast in the semi-solid state.

INTRODUCTION

This report is the second describing work conducted at Massachusetts Institute of Technology on Machine Casting of Ferrous Alloys. It is a part of a broad university-industry research activity with the other participants being Abex, General Electric, and Hitchiner Corporations. Separate reports describe the research at these other facilities.

The program is envisioned as a three to four year activity. A central concept of the research program is that radically new technology is required to make a die casting process economically viable for ferrous alloys. Work at Abex is aimed at a process that would be applicable to ferrous castings in the range of 25 - 50 pounds or larger in weight. Work at General Electric is towards a process applicable to superalloys. Hitchiner studies are aimed towards a process for making small castings - under about a pound, and work at M.I.T. is aimed at studies that would be applicable for castings of a wide size range, but with emphasis on the smaller sizes.

Emphasis of the work at M.I.T. is on development of a process or processes involving casting of semi-solid alloys. During the six month period of research covered by this report, emphasis has been on developing casting systems which combine (1) a method of producing a semi-solid slurry continuously, (2) a "gel" or "collection" chamber, and (3) a casting machine. A large number of castings were produced of a low melting point alloy, and of a copper base

alloy. A limited number were also produced of a ferrous alloy (Fe-2.5%C-3.1%Si). Other work reported is on development of a process for electromagnetically injecting semi-solid or liquid alloys into metal mold and on thermal analysis of mold behavior in casting of semi-solid ferrous alloys.

CHAPTER 1. LOW TEMPERATURE MACHINE CASTING SYSTEM

Summary

The low temperature casting system consisting of the continuous semi-solid slurry producer, "gel" chamber, and casting machine was used to cast about one hundred castings of Sn-15%Pb alloy. Detailed analysis of the castings carried out by X-ray radiography and optical metallography showed that the amount of both entrapped gas and shrinkage porosity decreased with increasing fraction solid in the slurry.

High speed motion pictures taken during the filling of a transparent die show that, compared to liquid metal, a slurry flows into the die more smoothly, entrapping less gas.

Introduction

A casting system for semi-solid slurries was described in an earlier report (1). The system consists of an apparatus that produces semi-solid slurry of a Sn-15%Pb alloy continuously or semi-continuously as needed, with the desired fraction solid, and a casting machine as shown schematically in Figure 1.

Continuous Slurry Producer

The continuous slurry producer, as described in a previous report (1), consists basically of a vertical tube through which metal flows while being agitated and cooled. The metal thus enters

the upper end of the tube as a liquid and emerges from the bottom as a partially solid slurry.

The heating coils of the mixing tube are now regulated by a proportional controller as determined by the output of a thermocouple in the lower part of the mixing tube. This allows the flow rate of metal through the slurry producer to be varied, or shut off temporarily, while still maintaining the desired output temperature and fraction solid of the slurry.

Previously, the mixing tube had been cooled by a flow of air through a surrounding jacket. A water cooling jacket has now been added over about one quarter of the length of the tube to increase the available cooling capacity. The increased cooling capacity makes possible higher slurry output rates.

Casting Machine

Approximately one hundred castings were made from Sn-15%Pb alloy in the completely liquid or semi-solid slurry state as listed in Table 1. The majority of the castings were made in an aluminum die with a volume of about one cubic inch. The overall size of these castings was approximately 2"x2½"x 5/16". A few castings were made in a steel die of about the same volume. The dies were used at room temperature or preheated to 100°C. The chamber pressures used to inject the metal were 200, 400, and 600 psi.

As shown schematically in Figure 1, the slurry from the continuous slurry producer is collected in an open ended steel cylinder in the heated "gel" chamber. If a high fraction solid slurry (f_s>~.4) is held in the gel chamber isothermally, it becomes

sufficiently rigid to be transferred to the casting machine. The cylinder containing the slurry acts as the shot sleeve of the casting machine. To cast the slurry without waiting for it to "gel", and to cast liquid or low fraction solid slurries, the ends of the cylinder are covered with a sheet of thin insulating material (e.g., paper).

Evaluation of Castings

The castings were examined for quality using optical metallography and X-ray radiography. Figure 2 shows a section of a casting made from a high fraction slurry.

X-ray radiographs of the castings were given ratings of from 1 to 5 for overall soundness, for the severity of entrapped gas, for the size of the largest gas hole, and for shrinkage. Figure 3 shows positive prints made from typical radiographs.

Table 2 lists the average ratings for the castings classified by the fraction solid of the material from which they were made. The average rating for overall soundness for high fraction solid ($> .5\ f_s$), medium fraction solid ($.3$ to $.5\ f_s$), and for zero fraction solid (liquid) castings were 2.9, 3.9, and 4.5, respectively. Similarly, each of the other rating scales shows an improvement in quality with increasing fraction solid. Table 3 and Figure 4 show the distribution of ratings for overall quality. Sixty-seven percent of the high fraction solid castings and 26% of the medium fraction solid castings were given ratings of three or better, but only 7% of the liquid castings received a rating of three.

Die temperature and injection pressure had no significant effect on soundness.

High Speed Motion Pictures

The die filling behavior of completely liquid and semi-solid slurries was studied using high speed motion pictures. A Red Lakes Laboratories Hycam 400 camera was used to film the casting machine die filling at the rate of 2500 pictures per second. The casting machine is shown in Figure 5a and the die alone in Figure 5b. The die was made with one steel die half with a machined cavity similar in size and shape to the die cavity used in the quality evaluation work. A one inch thick Pyrex plate was used as the opposing die half, and a 1/16 inch thick silicone rubber gasket was placed between the two die halves.

Figures 6 and 7 show sequences of frames taken from the high speed motion pictures. The surface of the liquid entering the die cavity is seen in Figure 6 to break up and splash off the opposite die wall. Figure 7 shows the relatively smooth flow of the slurry at similar stages in the die fill. This smooth flow results in the lower amount of entrapped gas observed in the slurry castings.

References

1. M. C. Flemings et al., "Machine Casting of Ferrous Alloys", Interim Technical Report, ARPA Contract DAAG46-C-0110, 1 January - 30 December 1973, prepared for Army Materials and Mechanics Research Center, Watertown, Mass.

TABLE 1. Castings Made for Evaluation of Soundness

No. of Castings Made	Fraction Solid	Injection Pressure (psi)	Die Temp (^{o}C)
16	0(liquid)	600	25
18	.3-.5	"	"
33	.5	"	"
3	0(liquid)	400	"
2	.3-.5	"	"
4	.5	"	"
3	0(liquid)	200	"
2	.3-.5	"	"
4	.5	"	"
3	0(liquid)	600	100
9	.3-.5	"	"
1	.5	"	"
3	0(liquid)	400	"

TABLE 2. Average Quality Ratings* of Castings

Fraction Solid of Cast Metal	No. of Castings Rated	Overall Quality	Gas Hole Severity	Maximum Gas Hole Size	Shrinkage
> .5	42	2.9	2.6	2.9	2.1
.3 to .5	31	3.9	3.5	3.7	2.2
0 (liquid)	29	4.5	4.6	4.0	2.5

* The rating scales used were from 1 (best) to 5 (poorest).

TABLE 3. Distribution of Overall Quality Ratings

Percentage of Group Receiving Rating

Rating	>.5 f_s	.3 to .5 f_s	0 f_s (liquid)
1	9.5	3.2	0
2	35.7	12.9	3.5
3	21.4	9.7	3.5
4	19.1	38.7	31.0
5	14.3	35.6	62.0

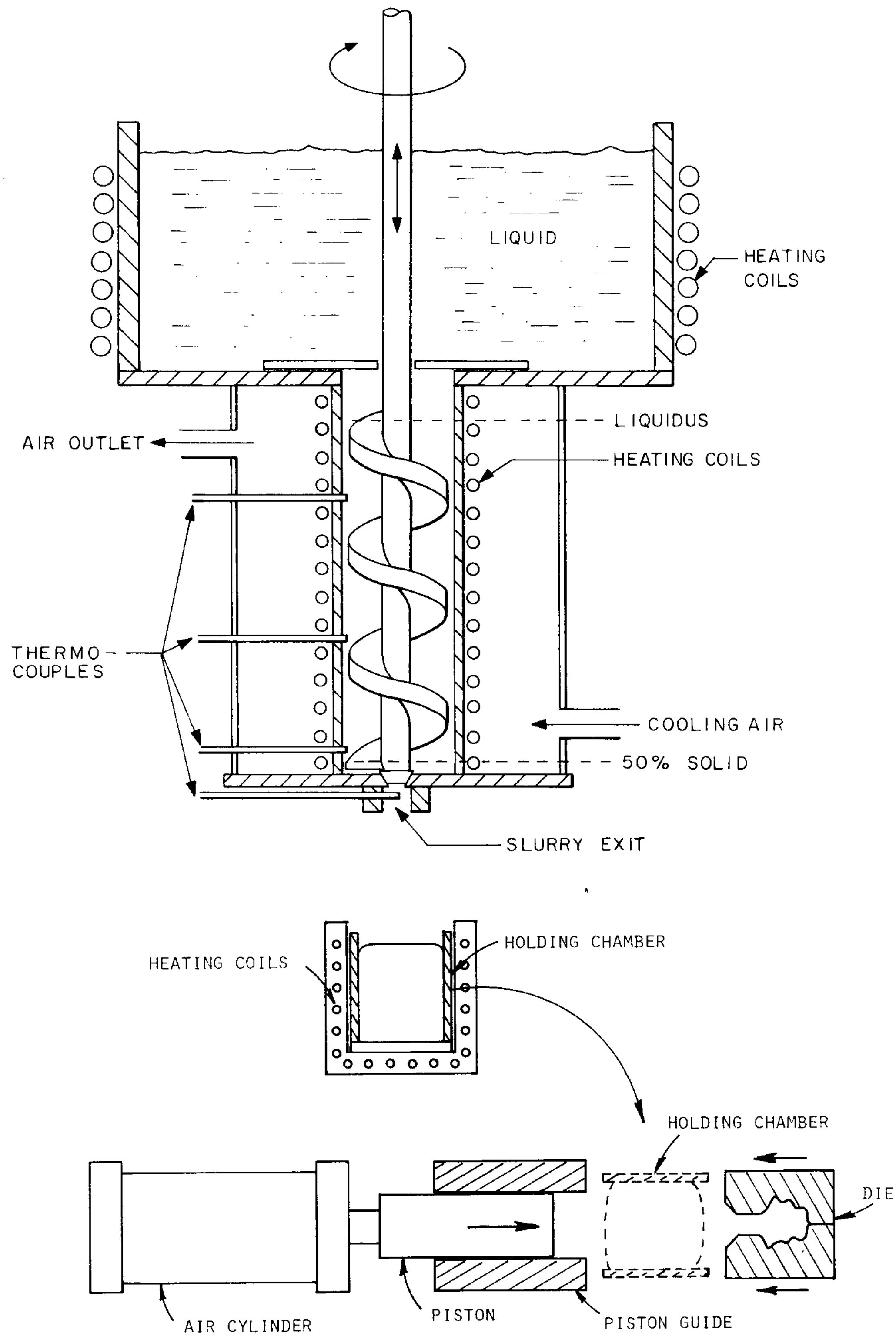


Figure 1: Schematic diagram of continuous slurry producer, "gel" chamber, and casting machine.

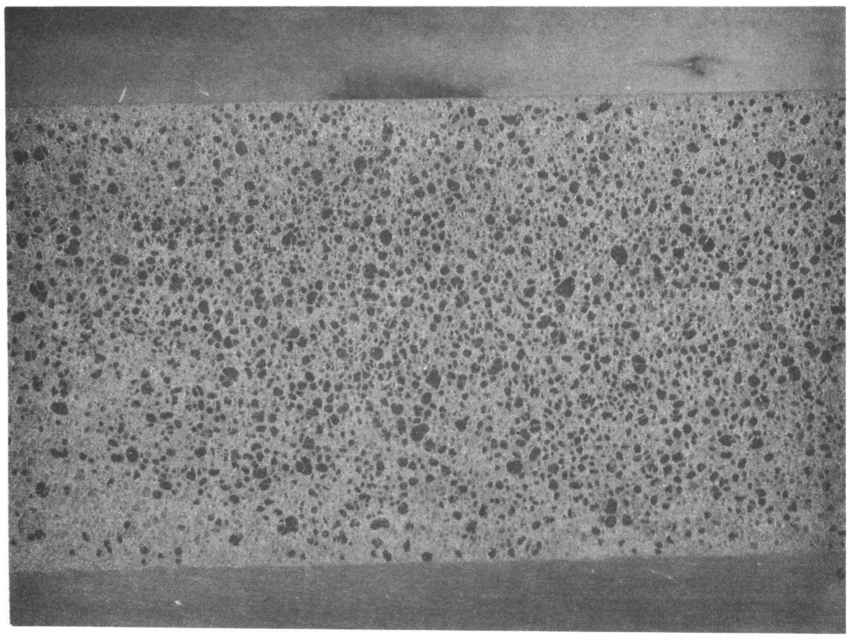
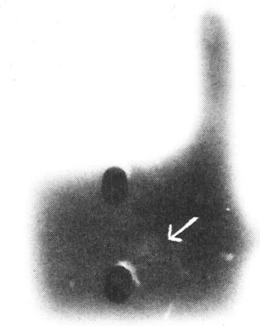
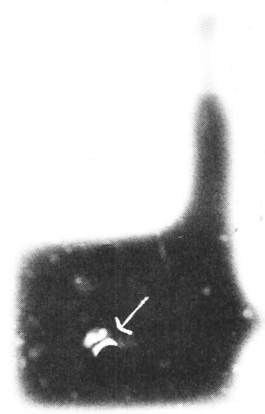


Figure 2: Photomicrograph of section of casting made from .60 fraction solid Sn-15% Pb slurry. Light and dark spots denote the primary solid particles; 8X.

Overall	2
Gas Hole Severity	2
Maximum Gas Hole Size	2
Shrinkage Porosity	2
Arrow: Type 2 Porosity	



Overall	4
Gas Hole Severity	5
Maximum Gas Hole Size	3
Shrinkage Porosity	1
Arrow: Size 3 Gas Hole	



Overall	5
Gas Hole Severity	5
Maximum Gas Hole Size	5
Shrinkage Porosity	Not Rated

Figure 3: Prints made from X-ray radiographs of castings and their ratings.

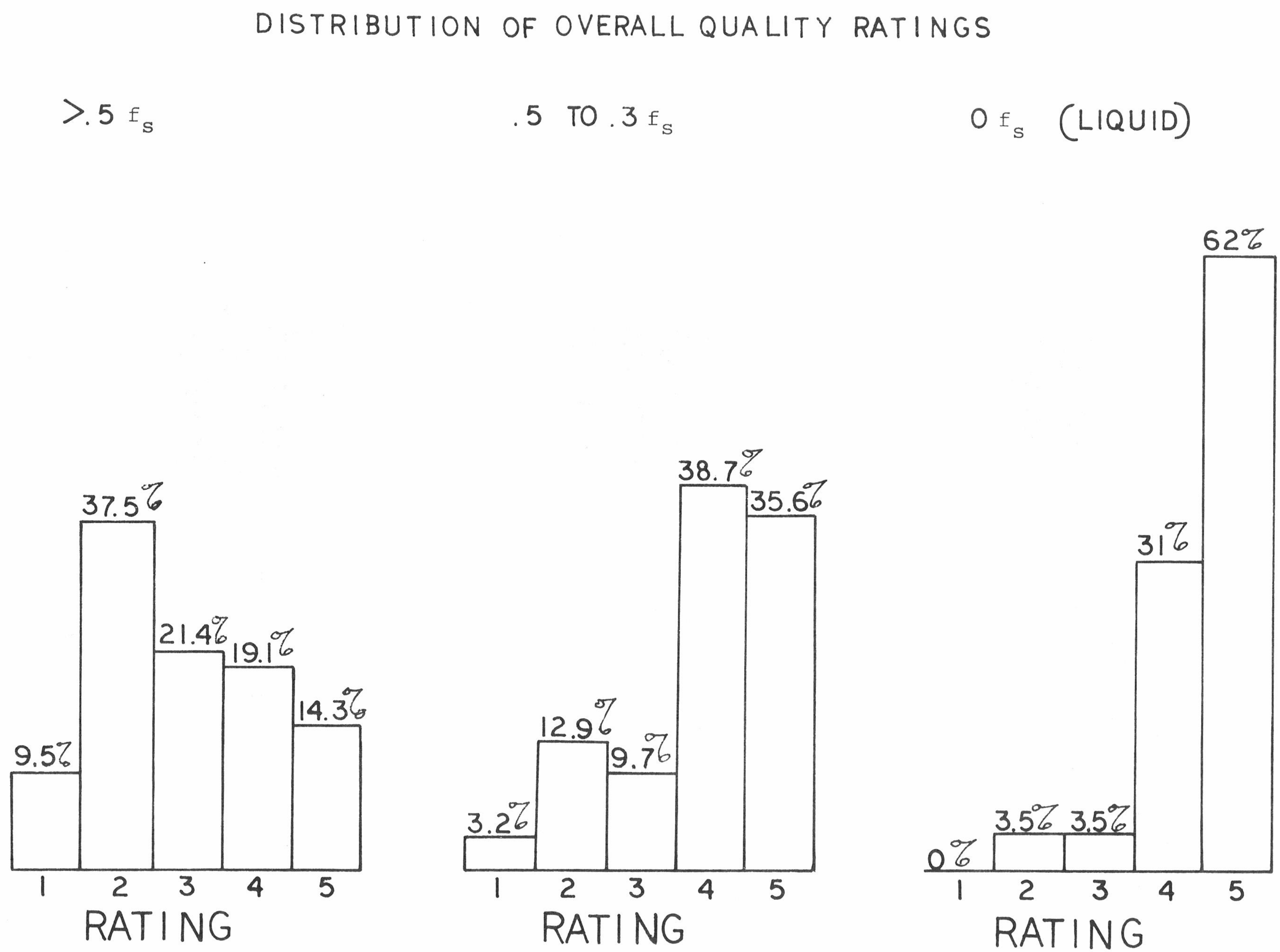
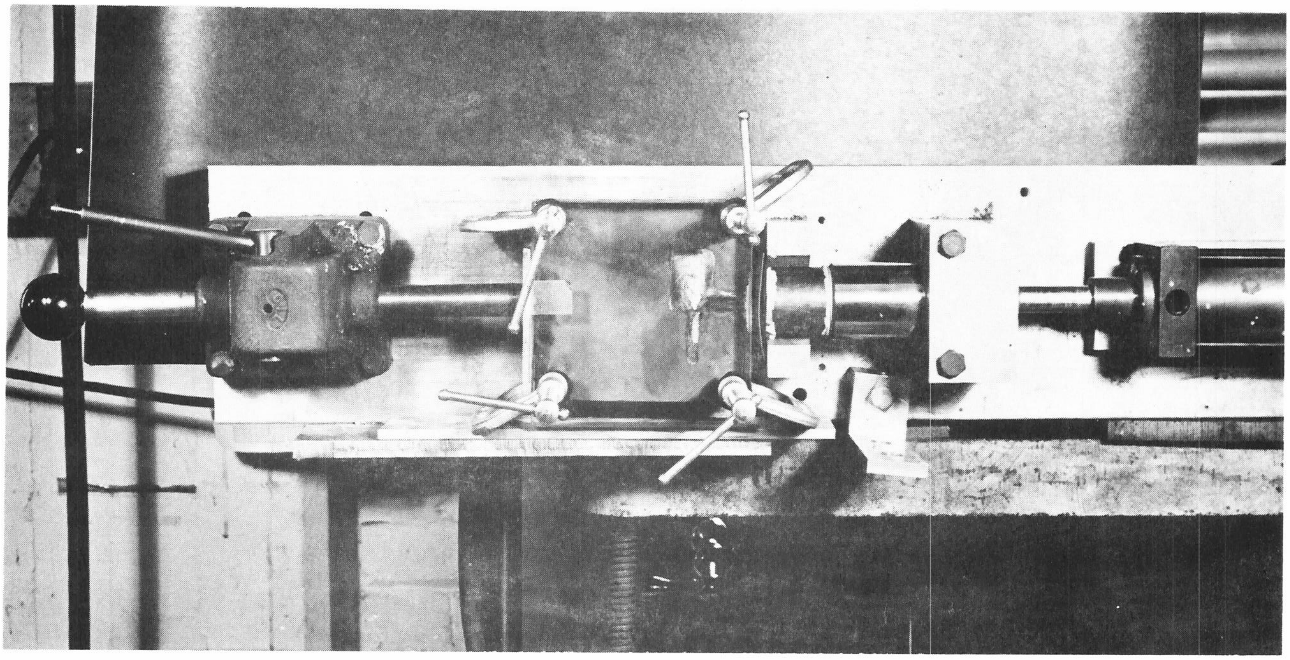
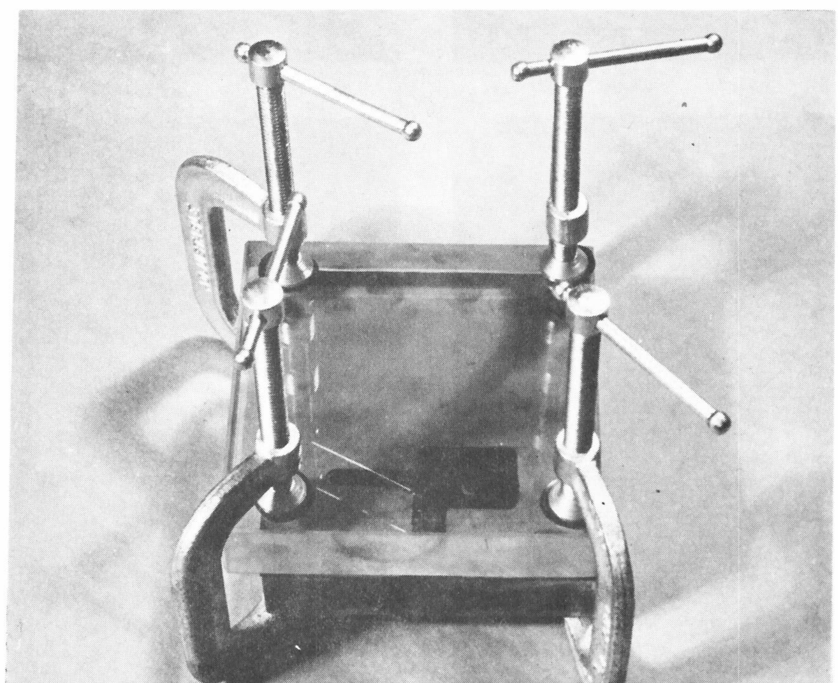


Figure 4: Percentage of castings in each group, grouped by fraction solid of the casting material, given a particular overall quality rating.



(a)



(b)

Figure 5: Apparatus used for high speed motion pictures of die; (a) casting machine with transparent die, (b) die.

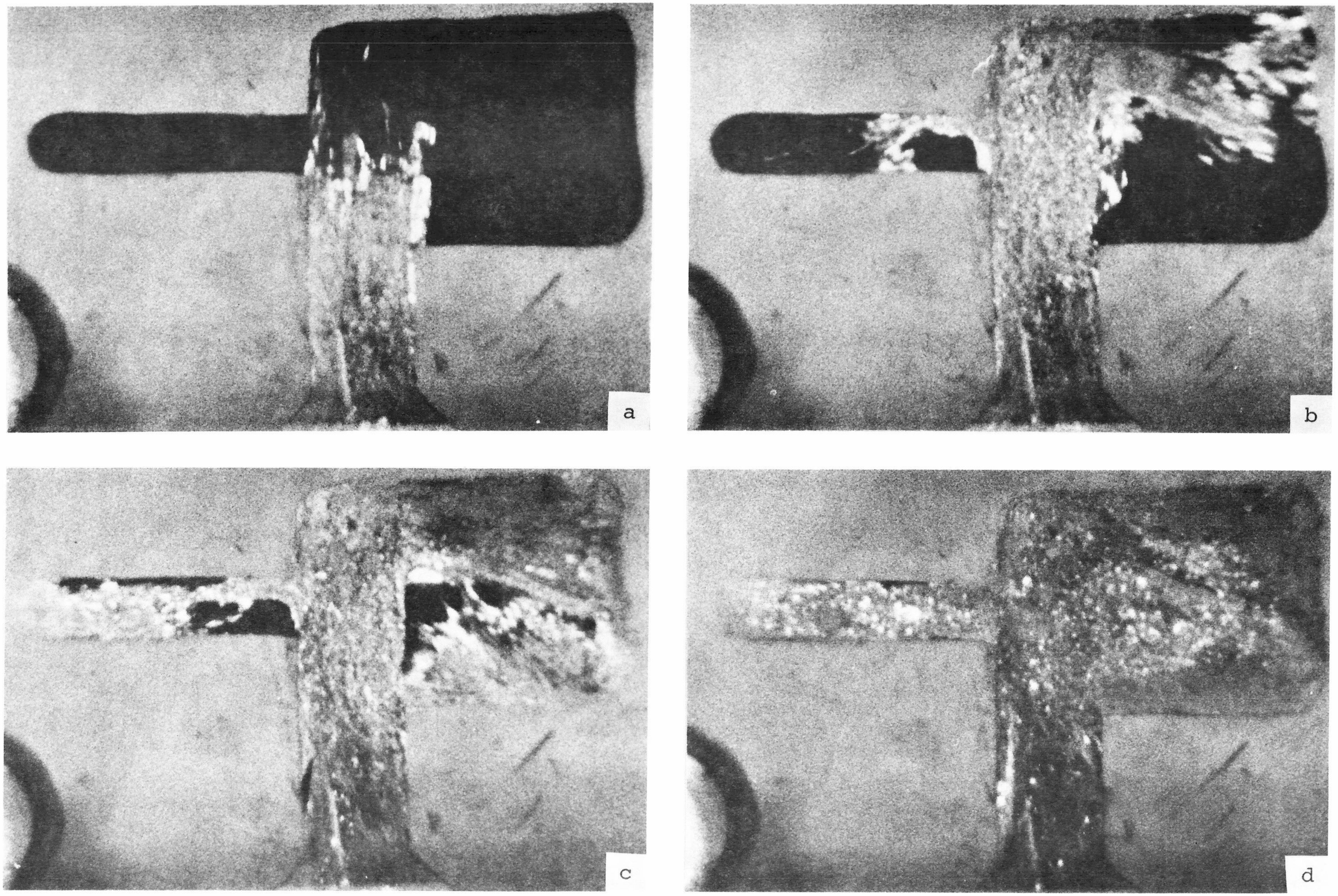


Figure 6: Sequence of frames from a high speed motion picture of a die filling with liquid.

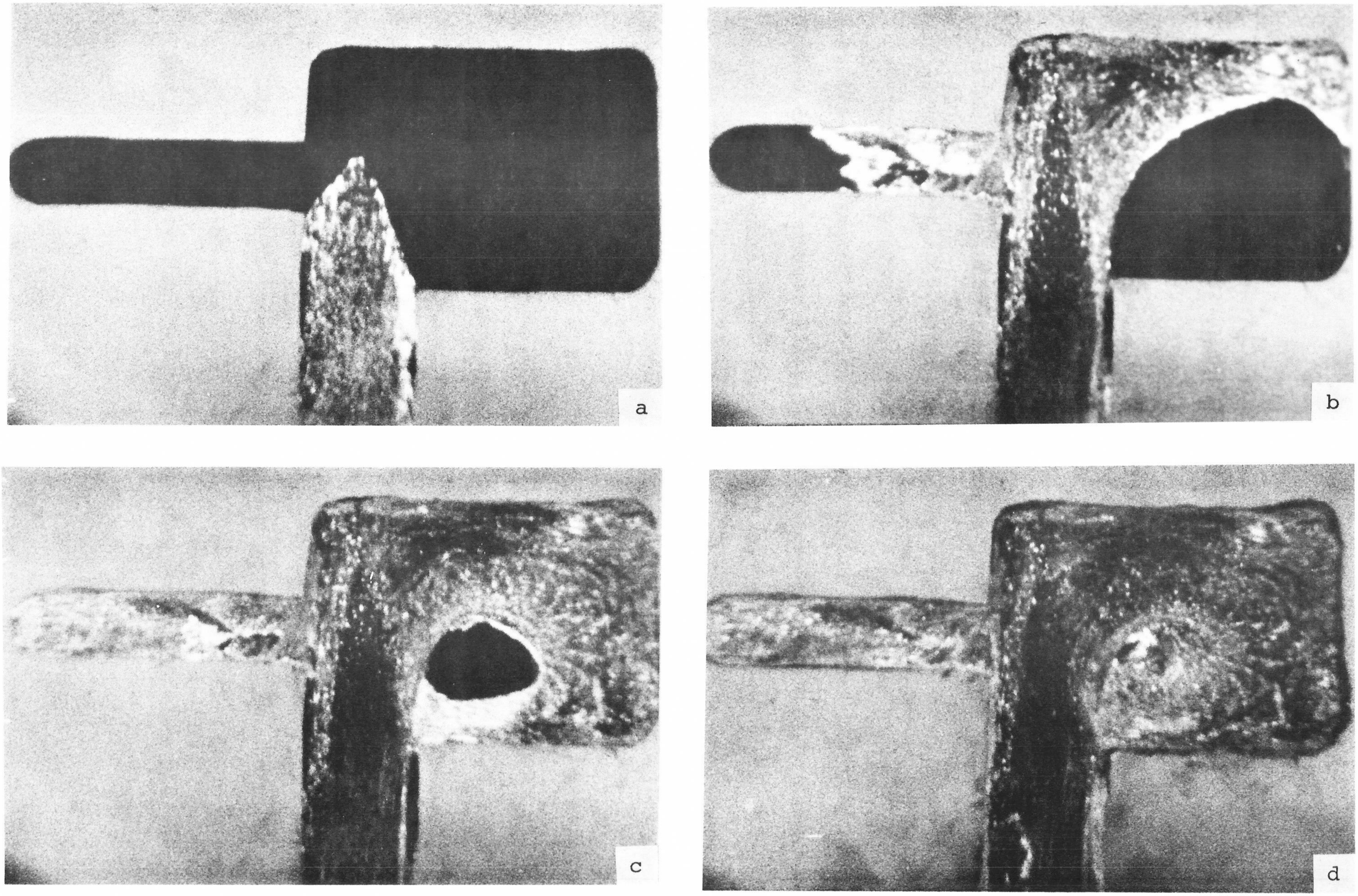


Figure 7: Sequence of frames from a high speed motion picture of a die filling with .56 fraction solid slurry.

CHAPTER 2. HIGH TEMPERATURE MACHINE CASTING SYSTEM - COPPER BASE ALLOY USED AS A MODEL SYSTEM

Summary

Following successful construction of an apparatus for continuous production of semi-solid slurries of ferrous alloys, an isothermal collection chamber and a low pressure die casting machine were built along the lines of those employed for low temperature alloys. The completed casting system was tested using copper base 905 alloy (88wt%Cu, 10wt%Sn, 2wt%Zn) as a model high temperature alloy system. Radiographic analysis of the castings made show that overall casting quality improves with increasing fraction solid in the slurry.

Introduction

The design, construction and successful operation with copper base alloys of the high temperature continuous slurry producer was reported previously(1). In this contract period, work was carried out to design, construct and operate a slurry collection chamber and low pressure die caster, suitable for ferrous alloys, along the lines of that described for Sn-Pb alloys(1). A successful evaluation of the completed casting system was made using copper base 905 alloy (88wt%Cu, 10wt%Sn, 2wt%Zn) as a model high temperature system. Some of this work has been extended to ferrous alloys as reported in Chapter 3.

Design and Construction of Apparatus

The design and construction of the high temperature continuous semi-solid slurry producer has been reported previously[1]. It consists of an integral reservoir and mixing crucible constructed from Vesuvius #235 ceramic (graphitised alumina). Figure 1 shows a schematic diagram of the reservoir and mixing chamber as well as the complete casting system. Figure 2 shows photographs of the apparatus. The top reservoir chamber is 3-5/8" in diameter and connects to the lower, 1-1/4" in diameter by 6" long mixing tube within which a rotating, vertically grooved rod provides sufficient shear to produce the characteristic non-dendritic Rheocast structure. Heating is by induction and is arranged such that about 100^{o}C superheat is achieved in the reservoir chamber with a variable temperature gradient in the mixing tube adjustable to produce the desired fraction solid. Flow from the mixing tube is via a 3/8" diameter central hole and is regulated by the separation between the stirring rod/ mixing tube bottom. A sheathed Pt/Pt-10wt% Rh thermocouple, located within the wall of the mixing tube close to the outlet is used to monitor the output of the continuous slurry producer. A detailed description of the apparatus and associated power supply were previously reported[1].

Two further pieces of equipment were constructed to complete the casting system. These comprise a "gel" chamber which serves as an isothermal holding chamber within which sufficient alloy is collected to make a single casting, and a low pressure casting machine. Both devices are similar in concept to that reported for low temperature alloys[1], and can be seen in Figures 1 and 2. The "gel" chamber

is heated by induction via a Vesuvius ceramic #235 susceptor. The susceptor is 1-3/8" I.D. and 4" long and can be sealed at the base with a graphite pedestal upon which sits an expendable Fiberfrax (a flexible ceramic) holding crucible 1" I.D. and 2-3/4" deep. The top of the "gel" chamber is partially sealed with an alumina cap and a 1" diameter silica tube which, during alloy collection, fits closely to the mixing tube base, eliminating spillage. When not in the collection position, immediately below the mixing tube outlet, the "gel" chamber is sealed with a cap placed upon the silica tube via which argon is passed slowly into the chamber. A Pt/Pt-10wt% Rh thermocouple, sheathed with fused silica, is fixed to this cap unit and permits measurement of the semi-solid alloy temperature just prior to casting. Subsequently the Fiberfrax crucible is removed from the "gel" chamber by lowering the graphite pedestal.

The die caster is driven by pistons powered with compressed nitrogen from a cylinder at a maximum operating pressure of 60psi, which results in a maximum injection pressure of ~1100 psi. The die halves, which are each heated with a tubular resistance heater located within the die body, are made from mild steel. These are clamped together during operation with a hydraulic jack (at ~2000 psi locking pressure). Die temperature is measured with a chromel/alumel thermocouple located within one die half close to the die cavity. The die cavity was machined to produce a modified form of a commercial part shown in Figure 3. In contrast to the low temperature unit, a movable shot chamber is employed which comprises a 1-1/4" I.D. steel sleeve. During operation the fiberfrax crucible filled with the semi-solid alloy is placed upon the injection piston and the shot sleeve is driven upwards to

seal against the clamped die halves, thus providing a shot chamber. The die is then filled by activating the injection piston which results in the destruction of the Fiberfrax crucible.

Experimental Procedure

Using copper base 905 alloy (88wt%Cu, 10wt%Sn, 2wt%Zn) as a model high temperature alloy, four experimental runs were made to evaluate the completed casting system. This alloy has a liquidus temperature of 999°C. An initial run of 11 castings was made to prove the equipment and to approximately locate the useful operating limits for the die temperature and fraction solid of the semi-solid alloy. In the three subsequent experimental runs, 40 castings were made with die temperatures of either 410-420°C or 450-455°C. Fractions solid were varied between zero (fully liquid, up to 100°C superheat) and 0.65. Injection pressure was 1100 psi. The injection speed was regulated by controlling the exhaust gas of the injection piston. Table I lists all the castings made and the respective experimental conditions prevailing. For most castings quench samples were taken either just before or after an alloy collection operation in the "gel" chamber. About 2 cm^3 of Rheocast alloy droplet was allowed to fall into a water quench tank.

At the end of this series, the die cavity shape was changed to that shown in Figure 4 and several castings were made. In this design, however, the runner length of the casting was prohibitively high and sound castings were not obtained.

Analysis

All the castings made were radiographed and assessed for size and distribution of gas and shrinkage porosity. This was accomplished in each case by comparison against a set of 5 chosen standards selected from the 51 castings made. Figure 5 shows some of the radiographic standards and their respective grading in each category. This grading is based on a points system, 0 representing the best and 5 the worst of each characteristic. Additionally, selected castings were sectioned for metallographic observation at the positions indicated in Figure 6 and the fractions solid were measured by point counting. This exercise was also performed on the equivalent areas of two castings polished on their flat faces to reveal the extent of any macrosegregation of primary solid particles. Where appropriate, the fractions solid of those castings selected for metallographic examination are also indicated in Table 1. Finally, all the quenched droplets taken were also polished and the fractions of primary solid measured.

Results

The point counting on the quenched droplet samples yielded the curve shown in Figure 7. This relates the measured melt temperature within a shot of alloy collected in the "gel" chamber to the fraction solid of the quench droplet sample taken just before or after collection. This curve has been used to translate all the measured melt temperatures to fractions solid as reported in Table I. Typical quenched droplet structures are shown in Figure 8. Comparison of this curve with the fractions solid measured from the castings shows that

the castings consistently give higher fractions solid than Figure 7 suggests, up to a maximum of approximately 0.65. Most likely this is the result of some solidification occurring during the transfer between "gel" and shot chamber and during time spent in the shot sleeve prior to casting. Cooling rates at the transfer stage have been measured to be approximately 40°C per minute. Both the fully liquid and the semi-solid alloys produced good casting surface quality. Positive prints of typical radiographs are shown in Figure 9 for both fully liquid (up to 100°C) and semi-solid castings. With the low pressure casting system employed, consistently poor radiographic quality was obtained from the fully liquid samples, whereas the semi-solid samples produced good castings with fraction solids up to 0.65. The results of the full radiographic assessment are given in Table I. Figure 10 shows the variation with fraction solid (melt temperature) of the overall radiographic rating, obtained by averaging the 3 individual components. For castings made into dies at 450-455°C and using the maximum injection speed available (castings 34-51), consistently improved radiographic quality was obtained with decreasing melt temperatures below the liquidus up to 0.65 solid. Figures 11 and 12 show that this improvement in quality is derived equally from reductions in both gas and shrinkage porosity. A micrograph of a typical region of a casting is shown in Figure 13. The point counting analysis has shown that generally a homogeneous distribution of primary solid particles was obtained throughout each cast part. These data are summarized in Figure 6 in which the % deviation from the average fraction solid is shown as a function of position within the cast part. It can be seen that most deviations from the average were of the order of 0-5%, although one or two castings showed larger discrepancies. Overall, an accumulation of primary

solid particles was evident in the biscuit just below the gate while the immediately adjacent runner area was depleted in primary solid. A minor redesign of the gating system employed would probably avoid this effect.

Conclusions

1. A casting system has been constructed for machine casting of semi-solid slurries of high melting point alloys. The system consists of a high temperature continuous slurry producer, a "gel" chamber, and a small die casting machine. The system has been successfully evaluated using a copper base alloy as a model system.
2. The results from 51 castings of the copper base 905 alloy show that when a semi-solid slurry is employed, both shrinkage and the size and distribution of porosity decrease with increasing fraction solid.
3. Metallographic examination of the castings show a generally homogeneous distribution of primary solid particles within the cast part.

References

1. M. C. Flemings et al., "Machine Casting of Ferrous Alloys", Interim Technical Report, ARPA Contract DAAG46-C-0110, 1 January - 30 December 1973, prepared for Army Materials and Mechanics Research Center, Watertown, Mass.

TABLE I

Casting No.	Estimated Fraction Solid at Casting	Die Temp. °C	Radiographic Rating Pore Size	Pore Distribution	Shrinkage	Overall Average
1-20	liquid	~400	~5	~4	~5	~4.5
21	0.07	405	5	3	5	4.3
22	0.24	416	5	2	4	3.6
23	0.03	411	4	3	4	3.6
24	0.46	415	5	3	4	4.0
25	0.42	418	0	3	4	2.3
26	0.45	416	4	4	4	4.0
27	0.42	417	4	4	5	4.3
28	0.42	414	4	2	4	3.3
29	0.46	416	4	3	5	4.0
30	0.44	416	0	3	4	2.3
31	0.46	403	4	3	4	3.6
32-33	liquid	~400	~5	~4	5	~5.0
34-43	liquid	~450	~5	~5	~5	~5.0
44	0.46	449	0	2	2	1.3
45	0.33	454	0	2	2	1.3
46	0.33	454	0	3	3	2.0
47	0.32	451	3	3	5	3.6
48	0.22	451	4	3	3	3.0
49	0.14	451	0	2	3	1.6
50	0.27	455	4	1	3	2.6
51	0.19	453	0	2	2	1.3

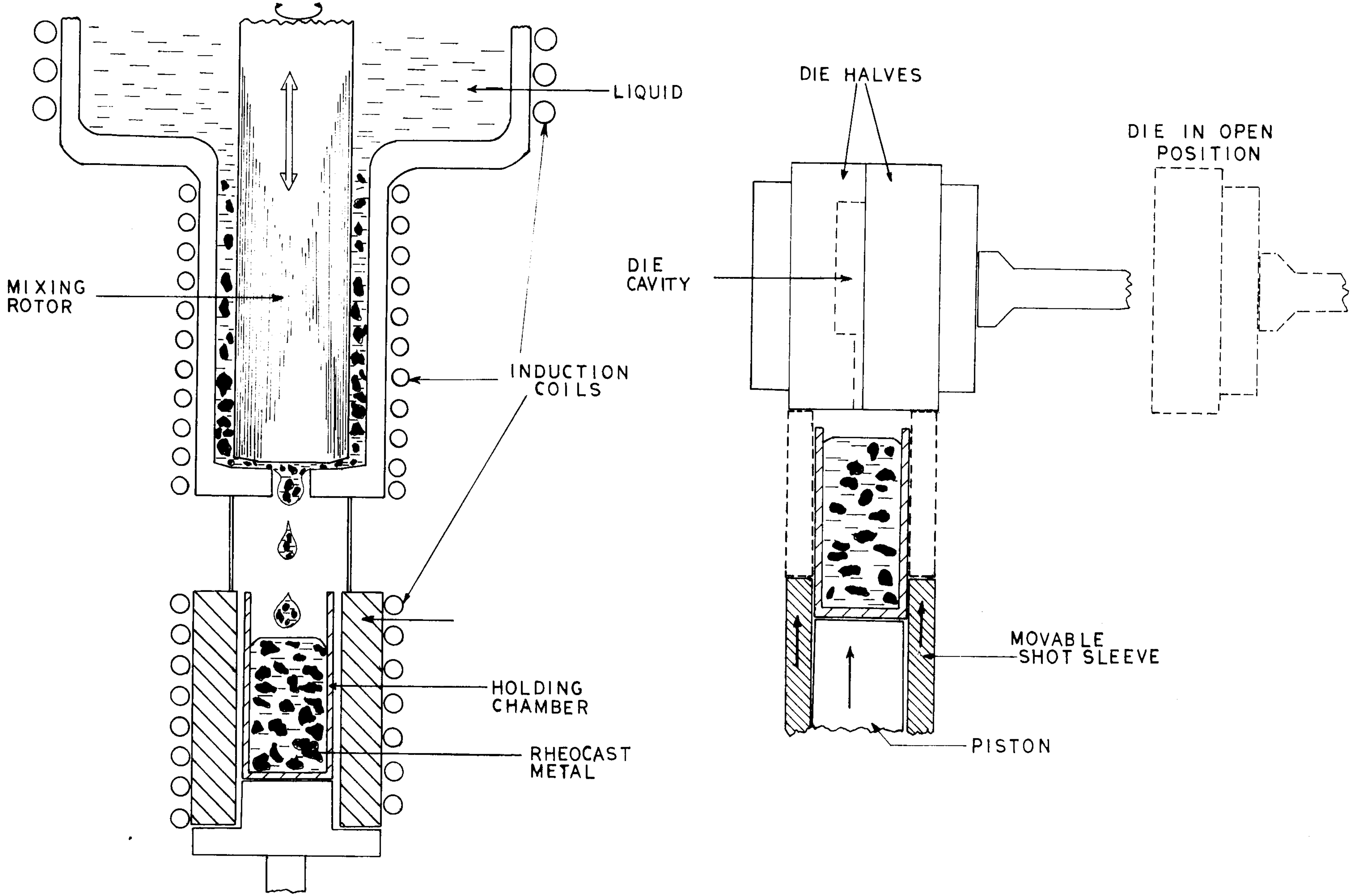
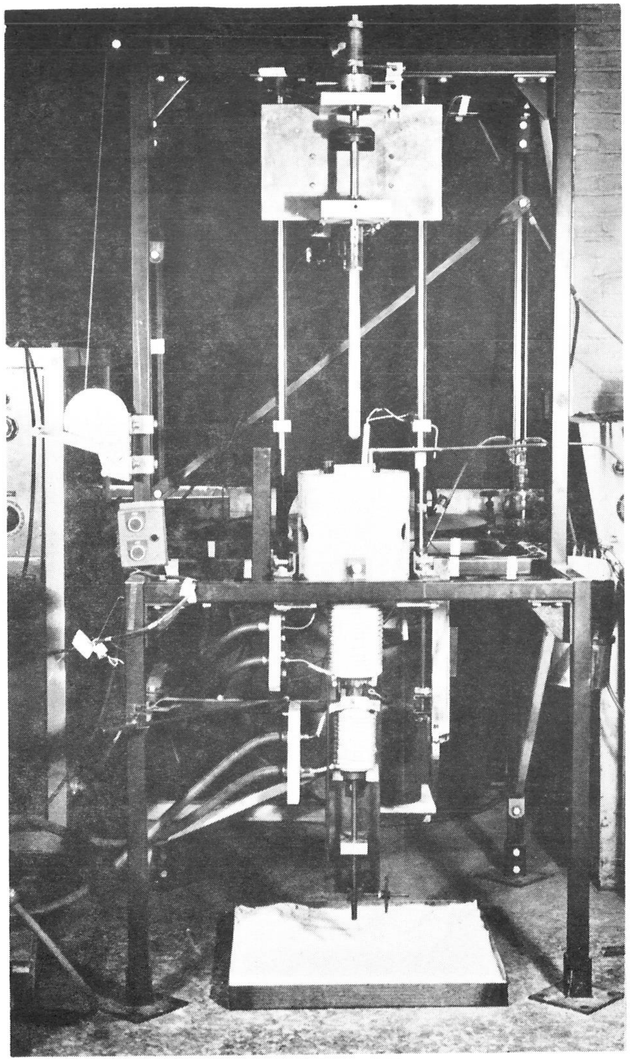
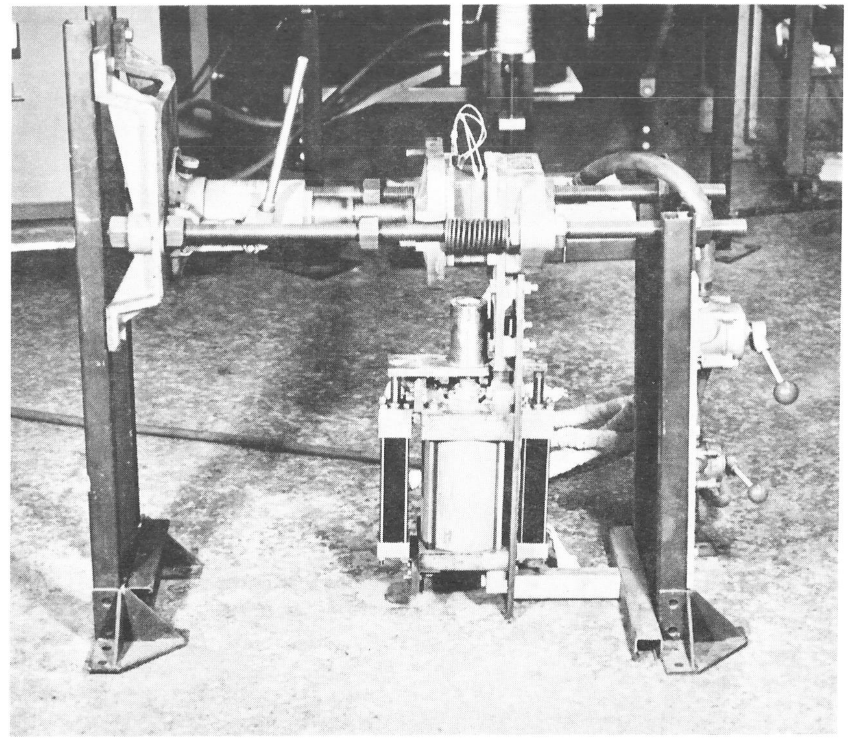


Figure 1: Schematic of slurry producer, holding chamber and die caster.



Continuous semi-solid slurry producer
and collection chamber beneath.



Low pressure die caster.

Figure 2: Photograph of the complete Casting System.

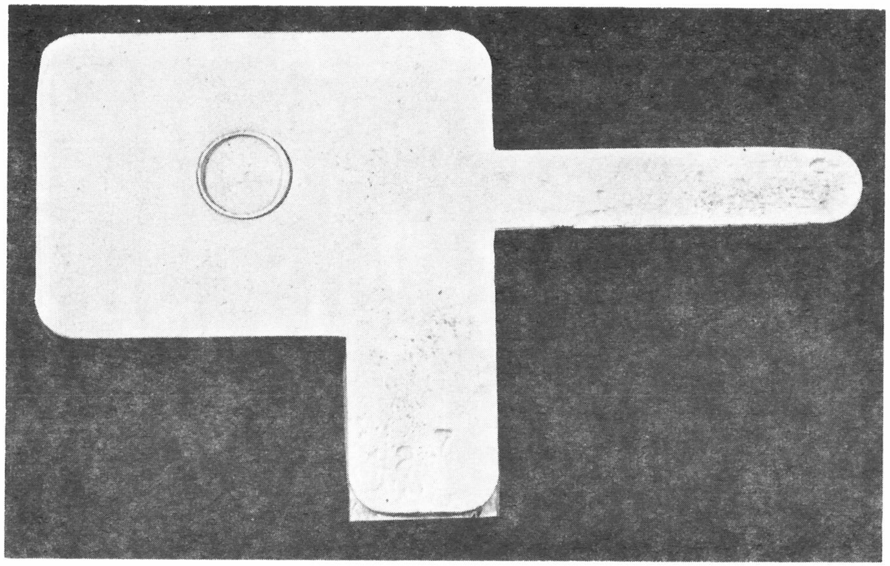


Figure 3: Casting shape used for the evaluation experiments.

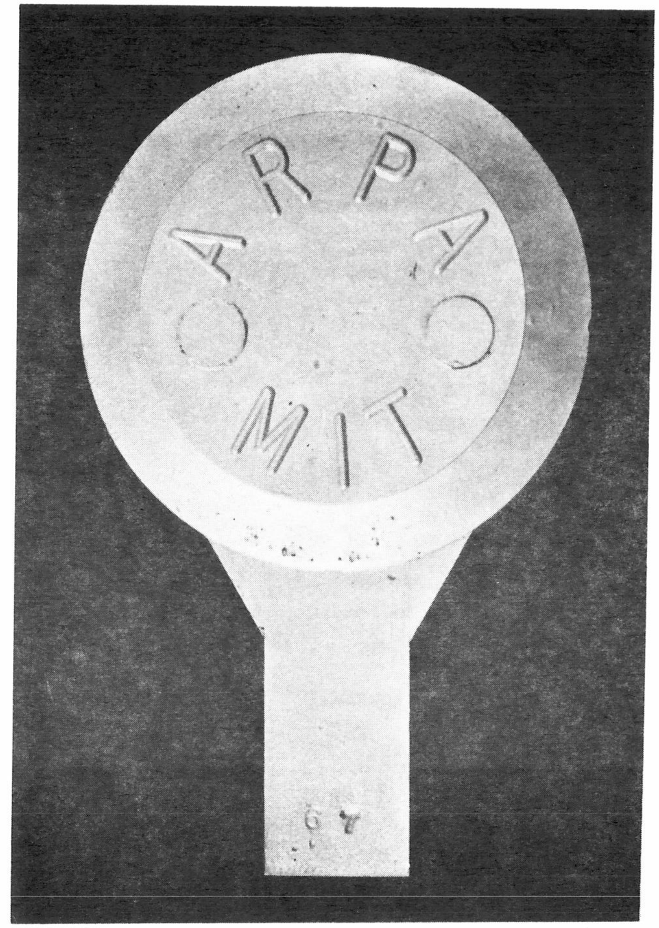
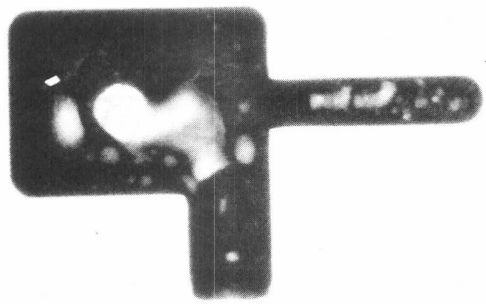
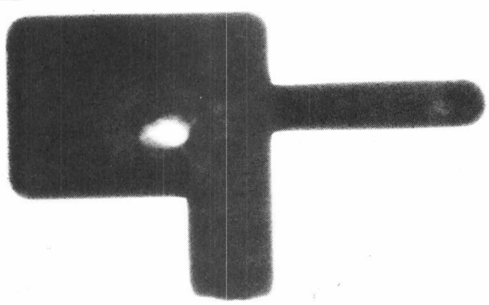


Figure 4: ARPA casting shape.

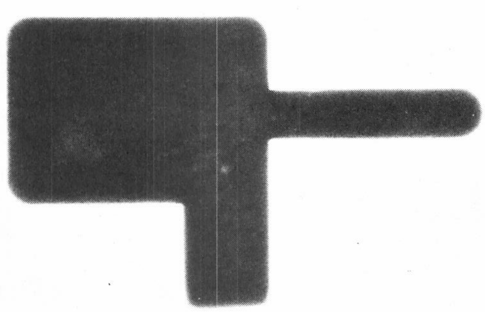
Category	Rating



Category	Rating
Overall	1.3
Distribution of Porosity	2
Size of Pores	0
Shrinkage	2



Category	Rating
Overall	3
Distribution of Porosity	2
Size of Pores	4
Shrinkage	3



Category	Rating
Overall	5
Distribution of Porosity	5
Size of Pores	5
Shrinkage	5

Figure 5: Examples of the Radiograph Rating System.

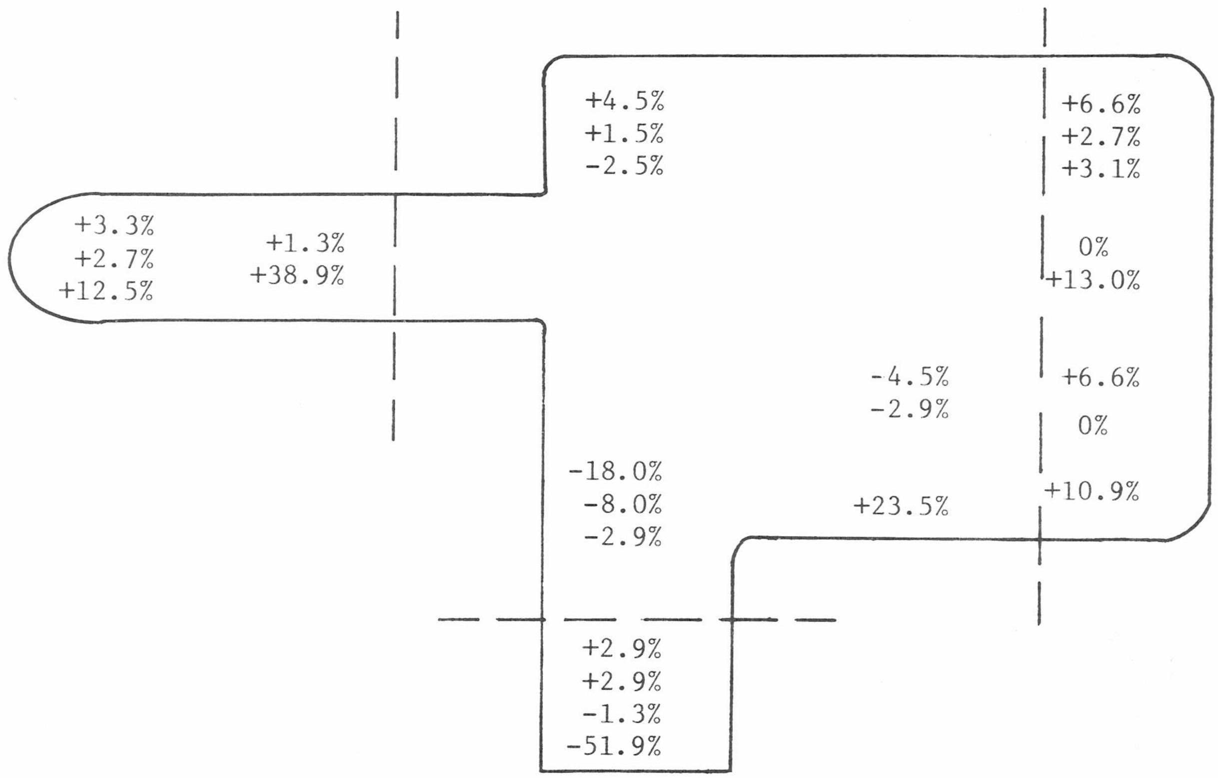


Figure 6: Schematic of casting showing % deviation from average fraction of primary solid as a function of position. Dashed lines indicate the actual location of the metallographic sections examined.

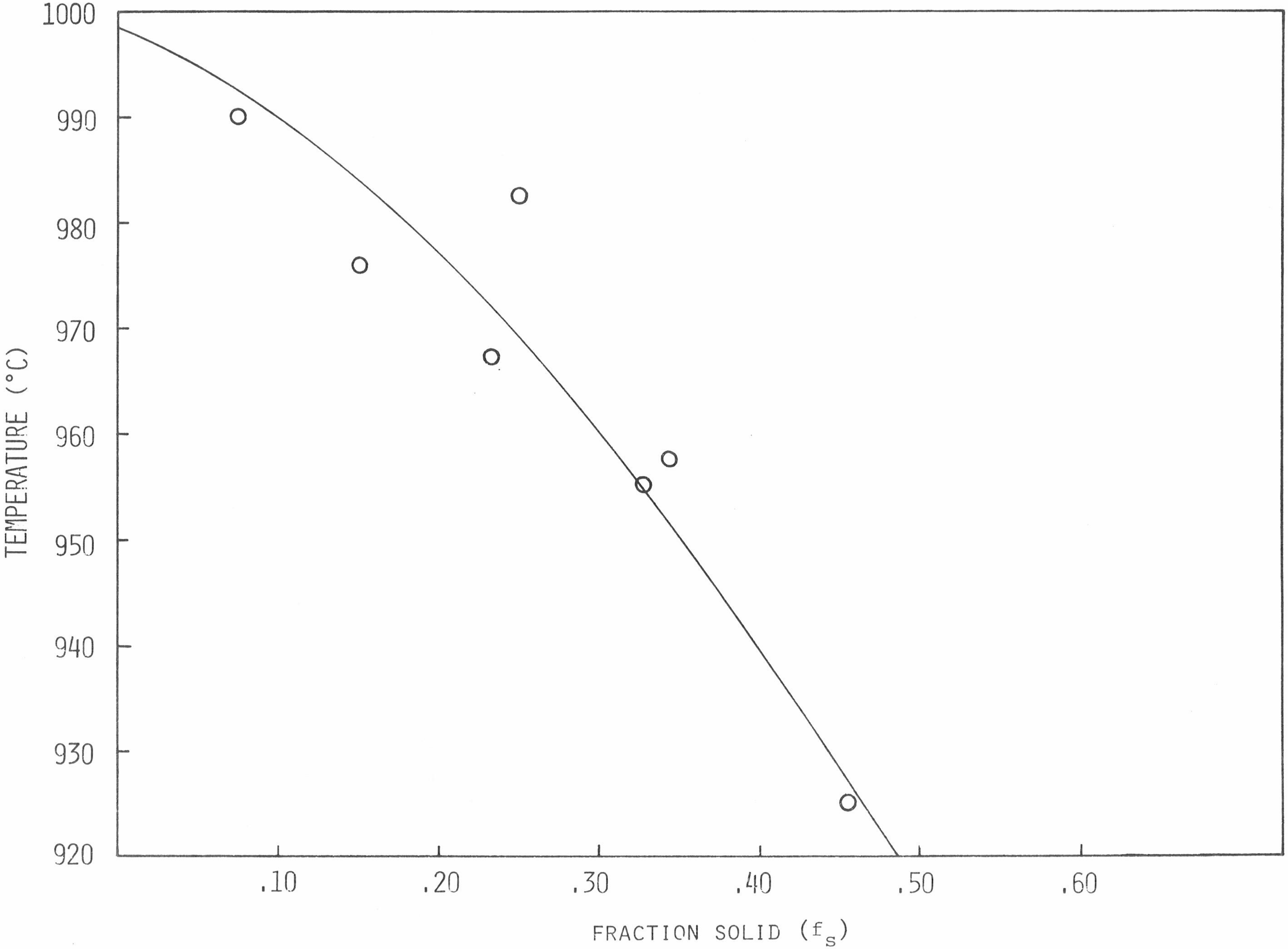
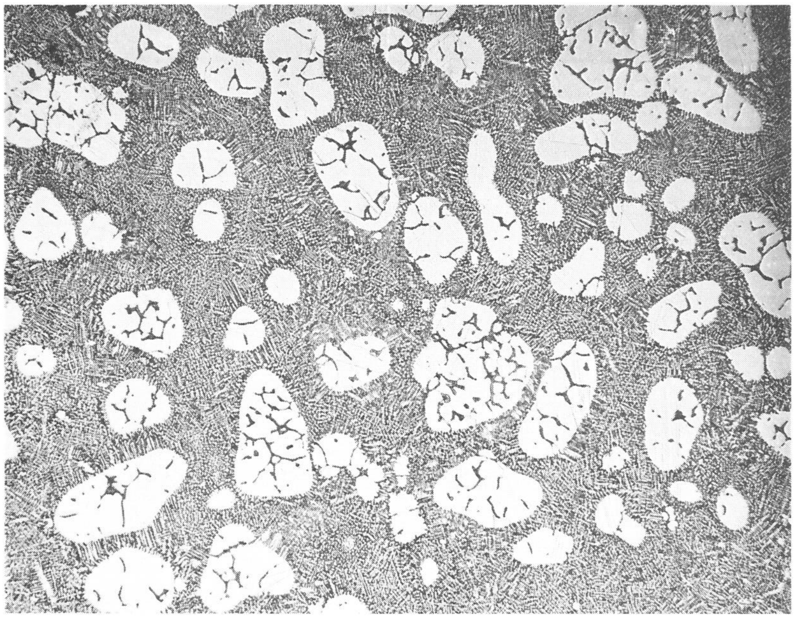
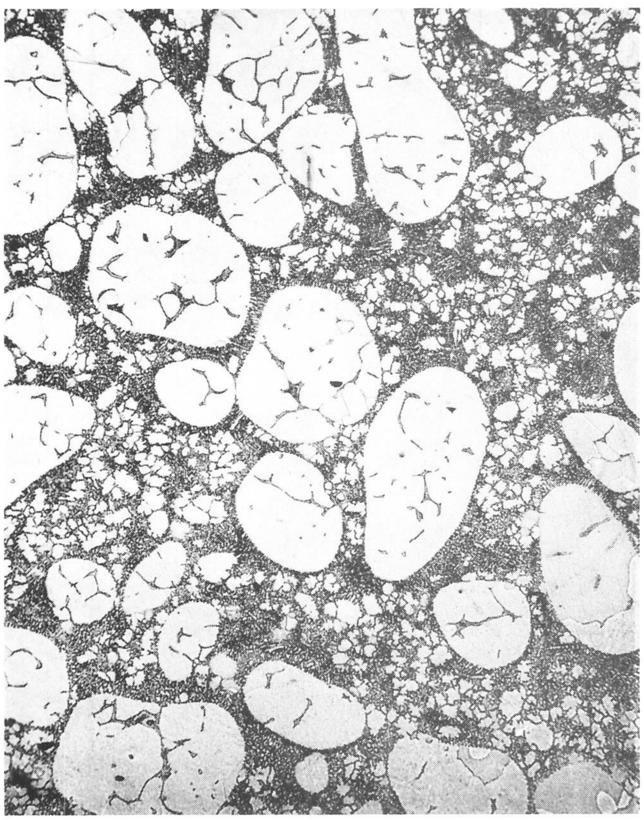


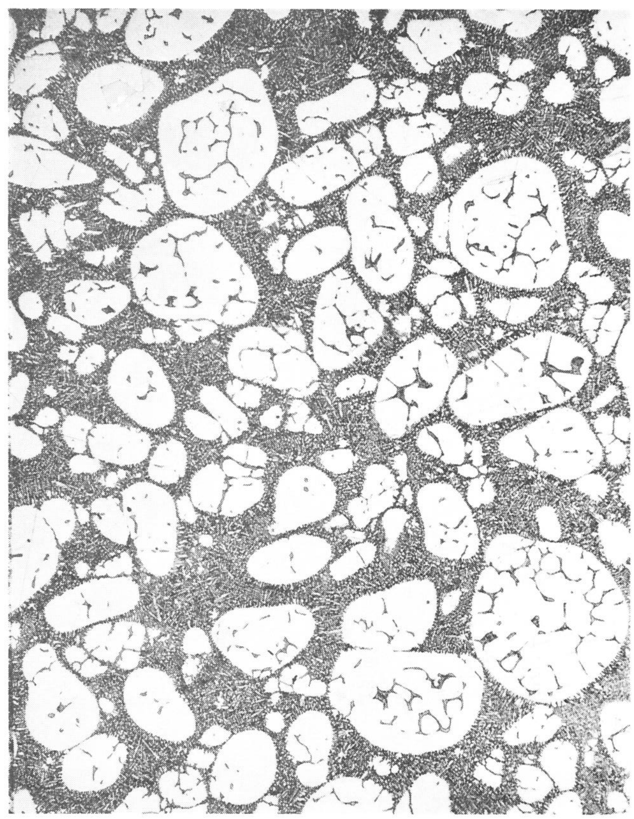
Figure 7: Fraction solid, f_s, versus temperature as determined from quenched droplets.



Melt temperature 983°C; 0.25 fraction solid.

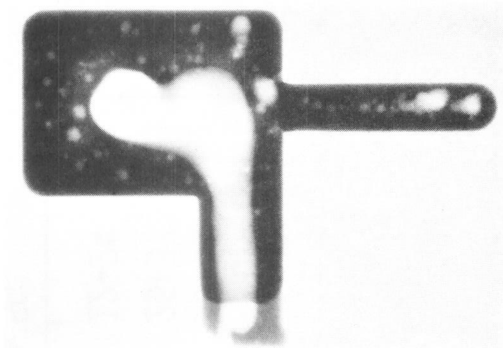


Melt temperature 957°C; 0.34 fraction solid.

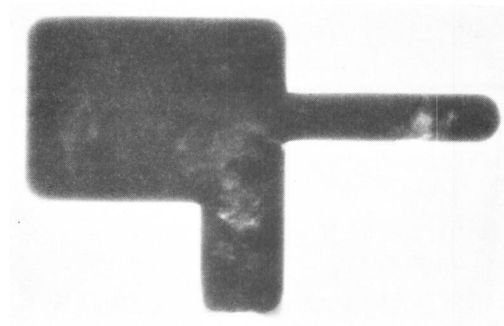


Melt temperature 925°C; 0.46 fraction solid.

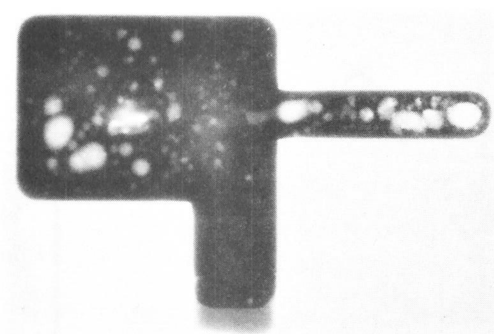
Figure 8: Typical micrographs of quenched droplets, 50X.



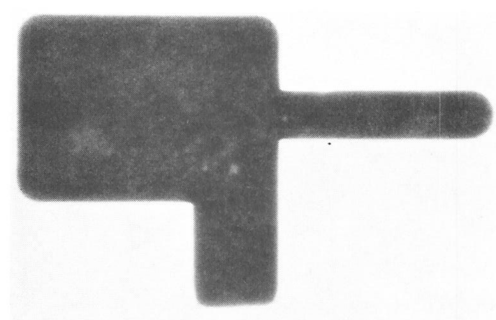
Completely liquid, $100^{\circ}C$ superheat



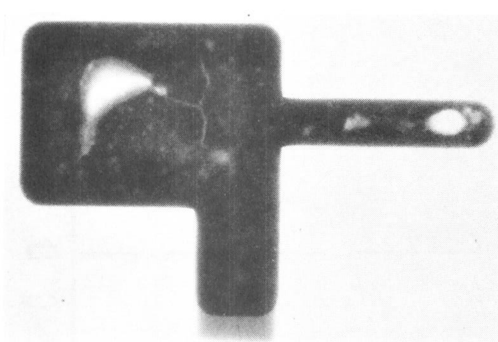
0.14 fraction solid



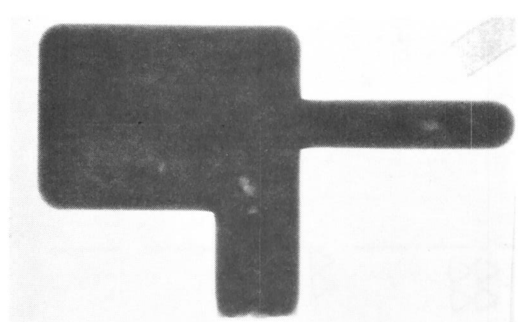
Completely liquid, $25^{\circ}C$ superheat



0.33 fraction solid



Completely liquid, $20^{\circ}C$ superheat



0.46 fraction solid

Figure 9: Radiographs of castings made from completely liquid and semi-solid 905 alloy.

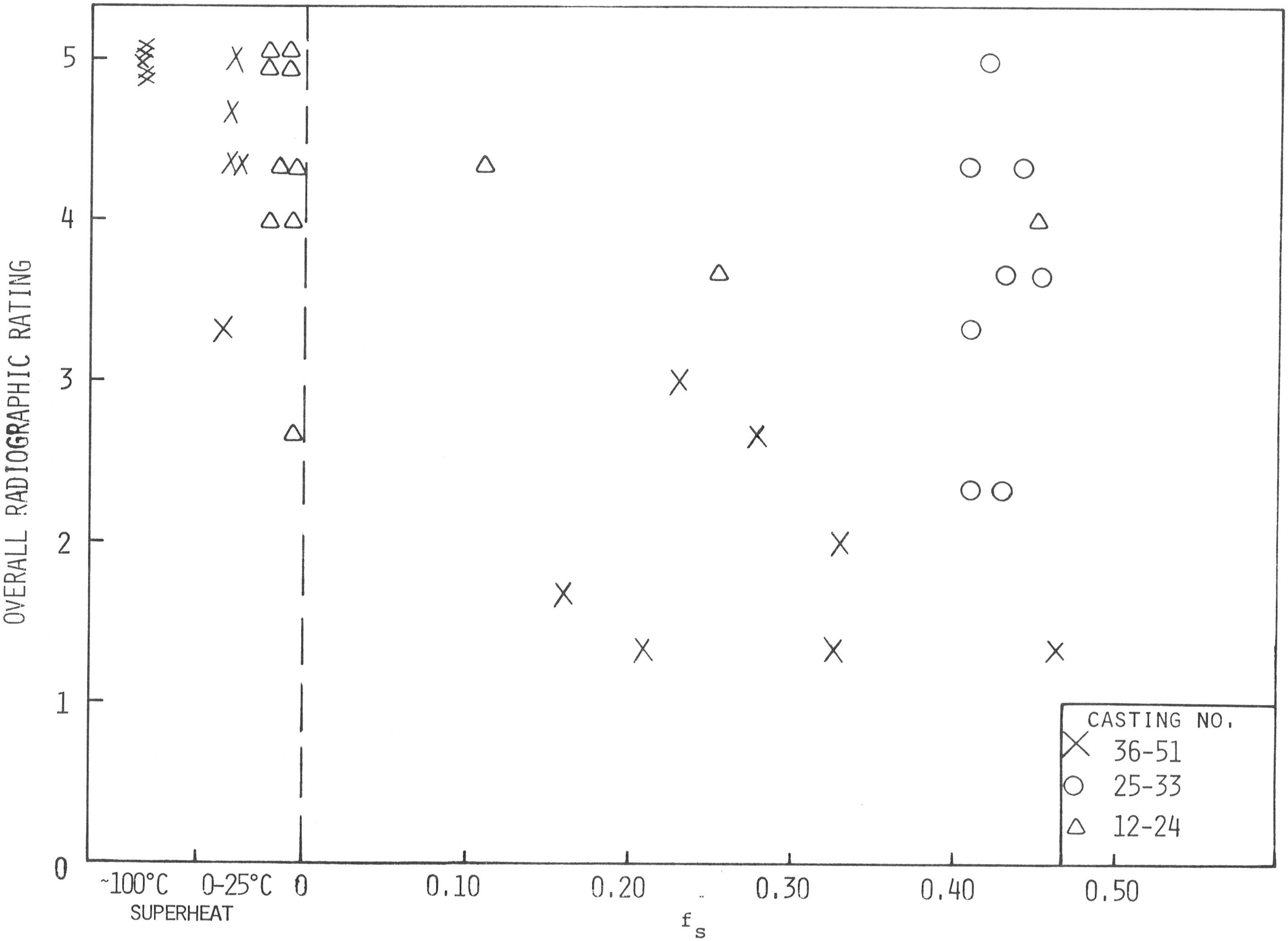


Figure 10: Overall radiographic rating versus fraction solid, f_s.

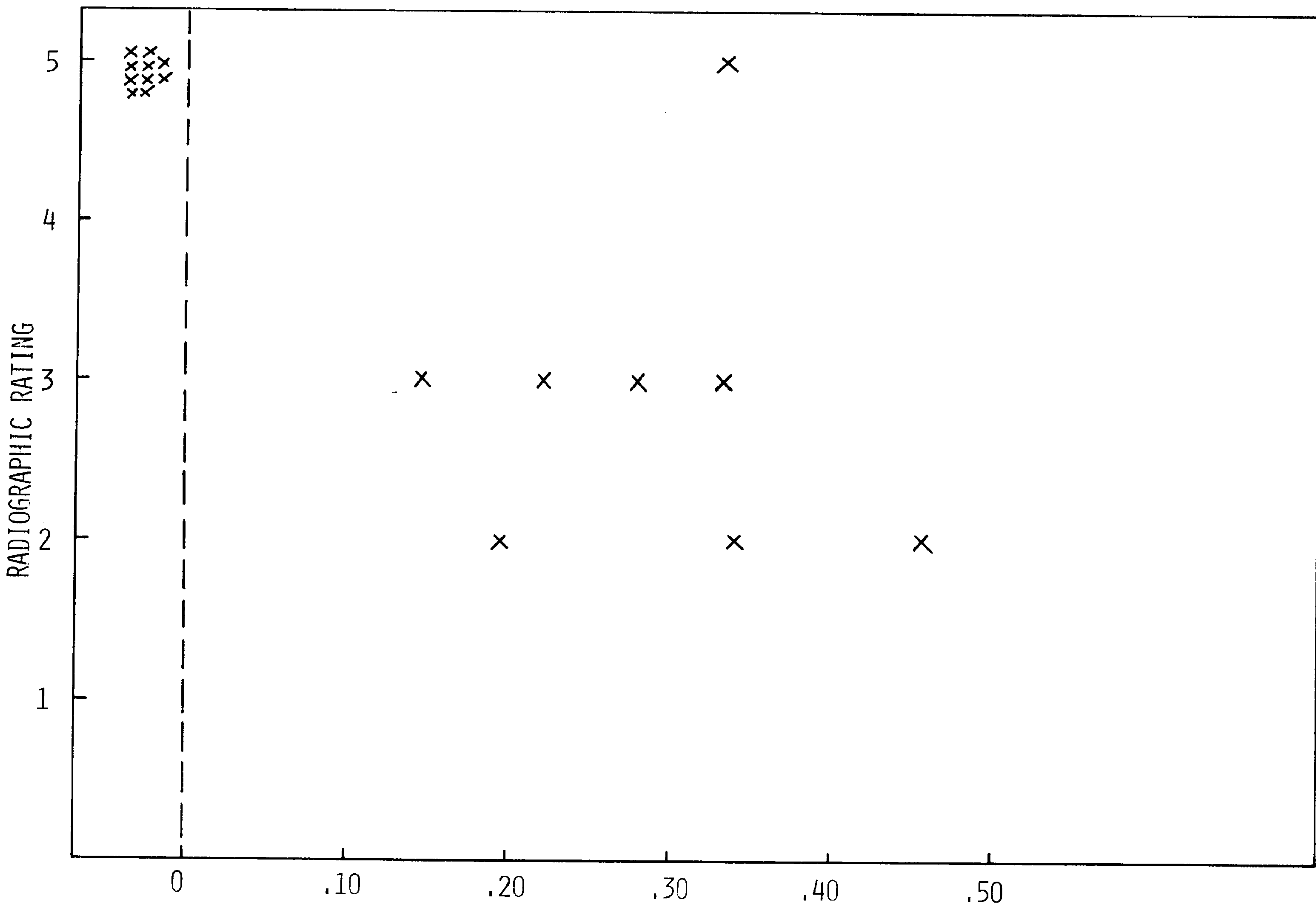


Figure 11: Variation of shrinkage porosity with fraction solid, f_s, castings 34-51.

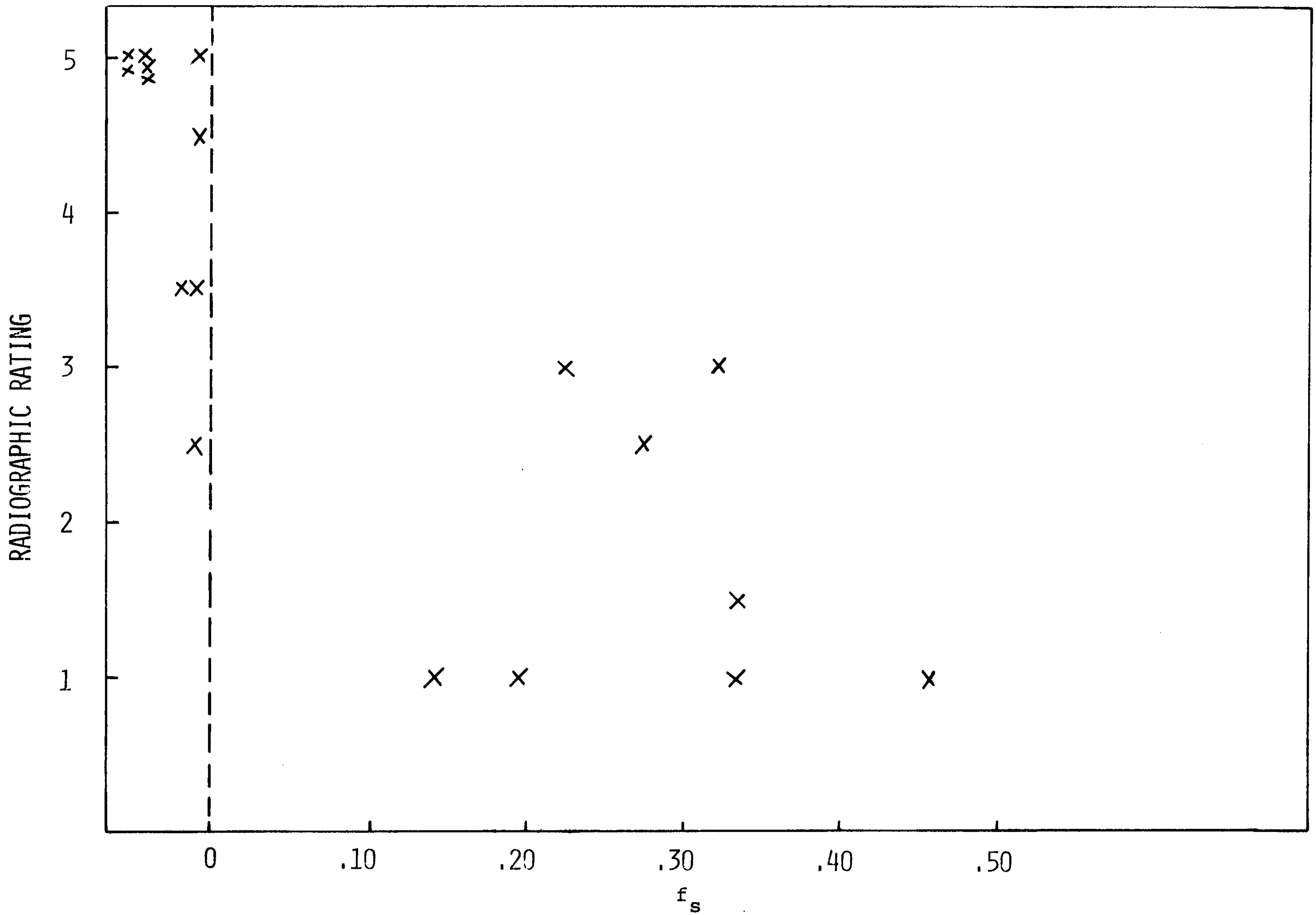


Figure 12: Variation of gas porosity with fraction solid, f_s, castings 34-51.

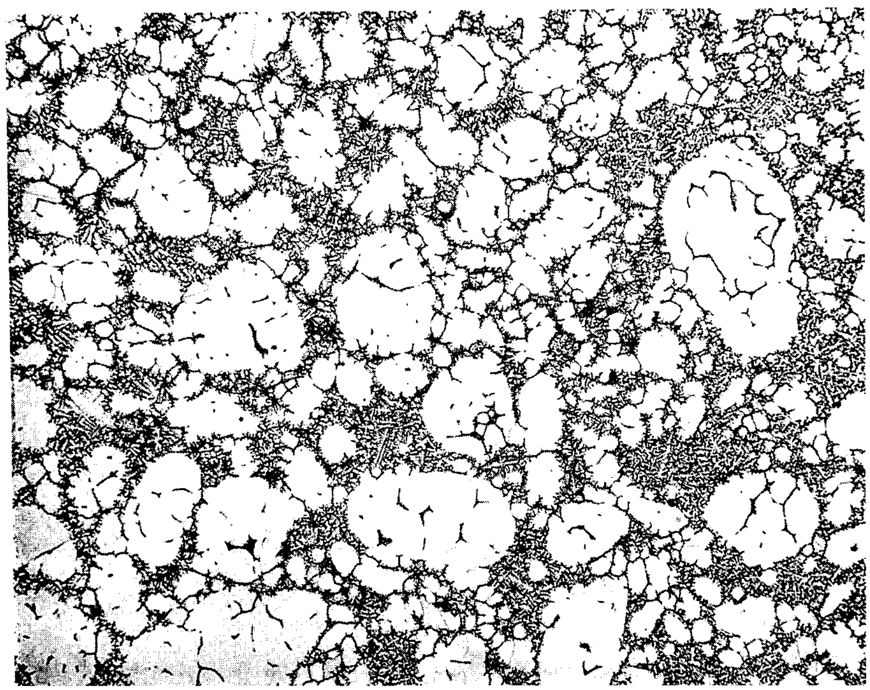


Figure 13: Typical micrograph of a Rheocast 905 alloy casting, 50X.

CHAPTER 3. HIGH TEMPERATURE MACHINE CASTING SYSTEM - APPLICATION TO CAST-IRON

Summary

Modifications were made of the casting system described in the previous chapter to permit casting ferrous alloys. Successful preliminary experiments were carried out with a hypoeutectic Fe-2.5%C-3.1%Si cast iron alloy.

Introduction

The high temperature casting system was tested with the copper base 905 alloy as described in Chapter 2. In that work, rotor material was graphite enabling extensive rotor design testing. However, in a ferrous alloy system, graphite is inadequate as a rotor material due to its solubility in the melt. In our previous report[1], a set of compatibility tests were described where various materials were used as stirring paddles in cast iron melts. The most promising materials were found to be silicon oxynitride and a pressed graphite-alumina mixture.

During this contract period, the high temperature casting system was tested using the hypoeutectic Fe-2.5%C-3.1%Si cast iron alloy. Different rotor materials were tested and some castings were made as described herein.

Apparatus Modifications

Rotors have been fabricated from the silicon oxynitride and pressed graphite-alumina materials and others, and their performance has been tested in the continuous slurry producer using the hypoeutectic cast iron alloy. The results of the performance tests to date are summarized in Table I.

At cast iron operating temperatures the heat losses at the exit section of the continuous slurry producer resulted in a tendency for the exit port to become plugged with frozen alloy, especially during semi-continuous operation. This situation has been remedied by the design change illustrated in Figure 1. A lower heating cylinder has been mounted abutting the bottom face of the mixing chamber. The cylinder is of the same graphite-alumina mixture as the crucible. The alumina shroud and induction heating coils have been extended to surround the heating cylinder. In operation the lower cylinder is induction heated to about the same temperature as the mixing chamber. This change has sufficiently cut heat losses at the exit port to prevent plugging at the port.

Preliminary Cast Iron Work

Hypoeutectic cast iron slurries of composition Fe-2.5C-3.1Si have been produced successfully in the continuous machine with the modification described above. Thus far, slurries have been produced using mixing rotors of silicon oxynitride and coated graphite (see Table I). The micrograph of Figure 2a illustrates the structure of the alloy slurry produced at about 0.35 fraction solid.

Castings have been produced from the cast iron slurries, Figure 2b, using this casting system. The operating procedure was the same as that described in Chapter 2.

In the near future, a series of cast iron slurry castings will be made under varied conditions in this system. Attempts will also be made to produce slurries in the continuous machine from several stainless steel compositions.

References

1. M. C. Flemings et al., "Machine Casting of Ferrous Alloys", Interim Technical Report, ARPA Contract DAAG46-C-0110, 1 January - 30 December 1973, prepared for Army Materials & Mechanics Research Center, Watertown, Mass.

TABLE I

MIXING ROTOR TESTS IN CAST IRON

Material	Composition	Supplier	Results/Remarks
Graphite-Alumina mixture	26%C, 58%Al_2O_3, 12%SiO_2, 2%CaO	Vesuvius Crucible Research	Insufficient mechanical strength
Silicon Oxynitride	85%Si_2ON_2, 12%Si_3N_4	Norton Co.	Negligible chemical erosion after ~3 hours; subject to thermal shock failure; seats well against graphitized Alumina crucible.
Molybdenum-Zirconia Cermet	40%ZrO_2, 60%Mo	Schwartzkopf Development Corp.	Significant pitting chemical erosion after ~3 hours; tendency to vibrate when seated against graphitized Alumina crucible.
Coated Molybdenum Zirconia Cermet	Cermet: Same as #3 Coating: Fibrefrax QF-180 (57%SiO_2, 41%Al_2O_3)	Same as #3 Carborundum Co.	Coating applied by dipping, ~.010" thick; chemical erosion at corners where coating is thin; coating spalls after one thermal cycle.
Coated Graphite	Graphite: ATJ Grade Coating: Same as #4	Graphite: Union Carbide Coating: Same as #4	Tip of rotor is Silicon Oxynitride; no axial grooves on rotor; coating applied by dipping, ~.010" thick; some slight pitting erosion beneath defects in coating after ~3 hours; coating spalls after one thermal cycle.

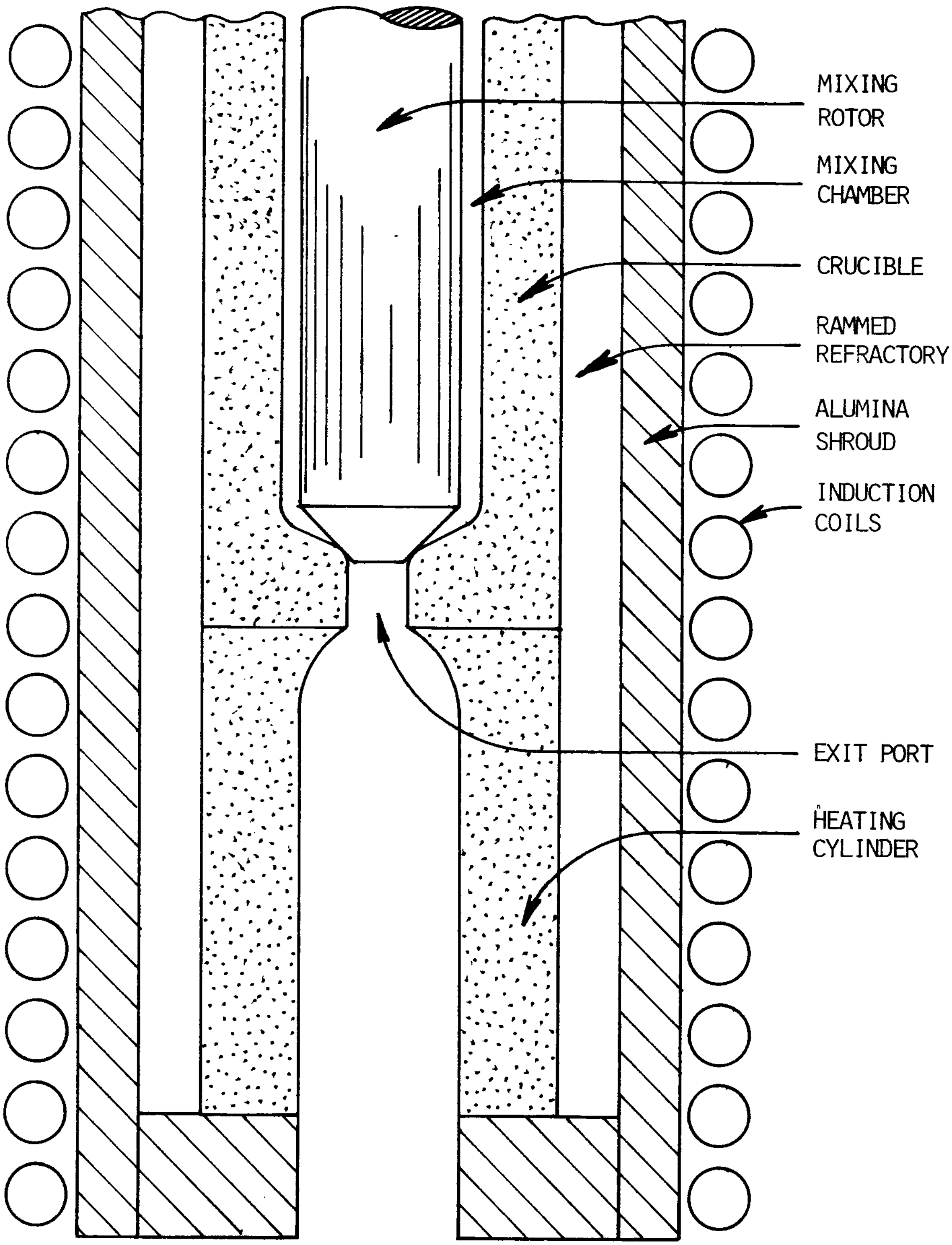


Figure 1: Schematic illustration of the lower portion of the continuous slurry producer as modified for cast iron slurry production.

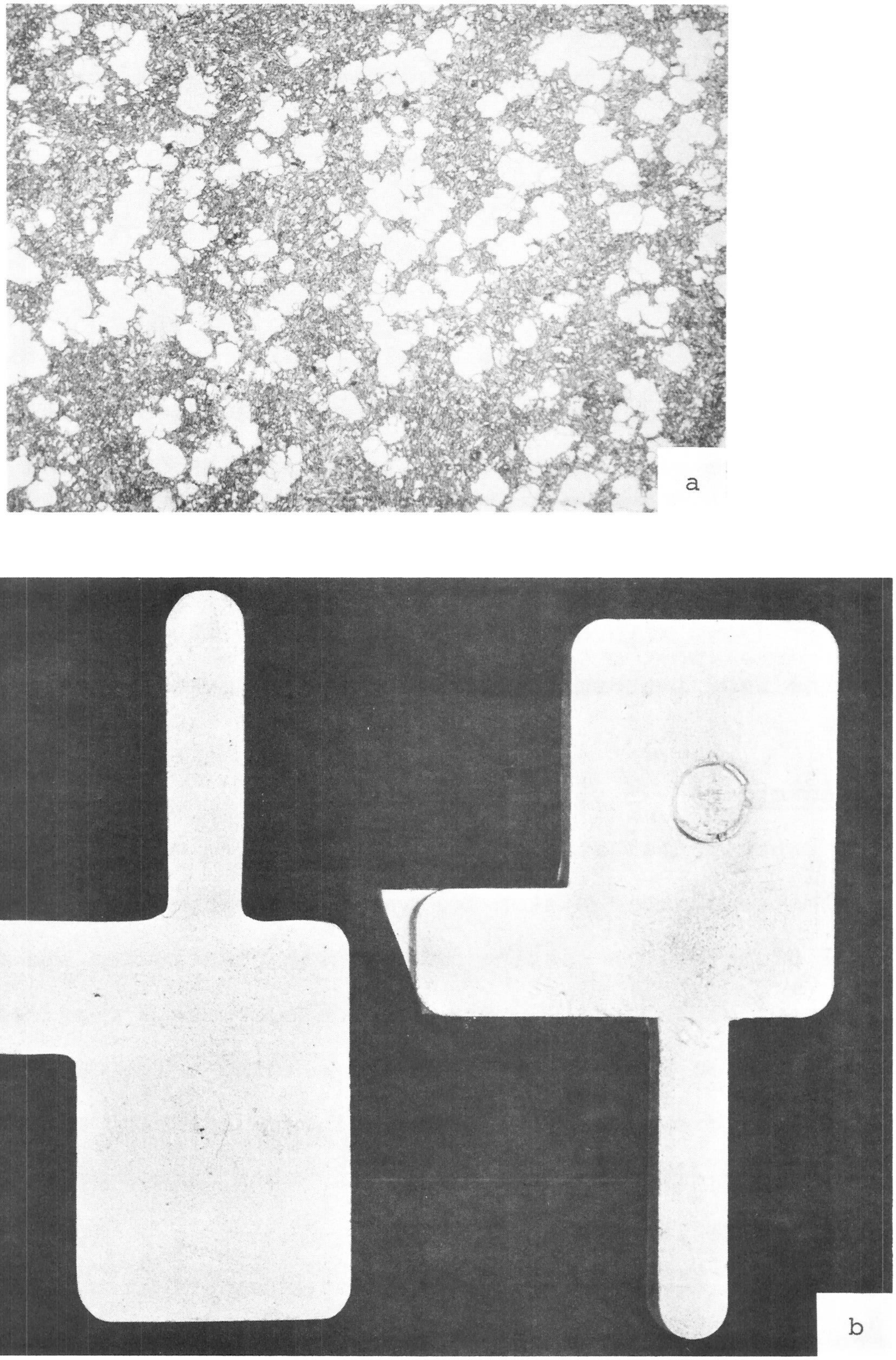


Figure 2: (a) Quenched microstructure of Fe-2.5%C-3.1%Si alloy slurry at about 0.35 fraction solid from the continuous slurry producer (50X); (b) castings produced from cast iron slurry (1.8X).

CHAPTER 4. ELECTROMAGNETIC INJECTION OF SEMI-SOLID ALLOYS

Summary

Work was continued to develop design parameters for an electromagnetic piston for rapid mold injection of semi-solid metals. The electromagnetic casting machine described earlier was modified. Modifications include an improved coil-die arrangement and development of a multiple discharge triggering system. Castings produced with a semi-solid aluminum alloy using the modified machine show improved die filling and reduced air entrapment.

Introduction

Experimental studies have concentrated on the development of an electromagnetic piston for rapid mold injection of semi-solid metal slurries. A casting machine was constructed and described in the previous report[1]. The machine contains a vertical tube furnace equipped with an air actuated sliding valve, a light source and electric eye sensing system, electronic delay circuitry, spark-gap trigger circuits, a copper wound coil, and a split graphite mold, Figure 1a.

To improve casting quality, major modifications of the apparatus were made during this contract period, Figure 1b. The modifications include a toroidal coil aligned vertically with respect to the die, and the use of multiple capacitor discharges to produce injection into the die. Also, a more complex die configuration consisting of a single down gate with one side arm was constructed and used.

Coil Die Geometry

Refinement of the coil-die alignment and geometry was necessitated by serious flaws in the original apparatus. One disadvantage of the old arrangement of coil and mold was the difficulty in achieving good electrical coupling between the coil and the semi-solid slug. In addition, owing to the flow pattern of current induced by the original spiral-pancake coil, severe metal spray was encountered. The basic issues involved in achieving good coupling were discussed in the previous report (1).

In the present design, metal propulsion occurs only in the axial direction. Furthermore, the alignment of the die and semi-solid slug along a mutual axis of circular symmetry promotes an improved metal flow pattern in the die accompanied by a reduction in entrapped air. This arrangement also reduces system sensitivity to improper timing. Originally, if the delay circuitry was incorrectly adjusted, the slug would strike the die mouth high or low creating an off centered casting with macroscopic voids. The modified machine will produce a casting with all timings such that the slug is below the midplane of the coil during discharge. Finally, gravity can be employed to introduce the semi-solid slug into the die.

Multiple Discharge System

Prior to this contract period, the work at M.I.T. done on magnetic injection of liquid or semi-solid alloys into die cavities

was performed with single-shot impulsive capacitor discharge devices. The limitations of this method became clear with experience gained during the last quarter, and a multiple-shot device was constructed to circumvent these difficulties.

The most basic flaw of the single pulse system is that it concentrates the entire discharge into a very brief amount of time, leading to extremely high transient forces in the discharge coil. Spreading this impulse out among four pulses divides the peak force by four and lengthens coil life dramatically. There are also fluid mechanical disadvantages to using one large pulse. The tendency of the metal surface to splash back towards the coil is greater with a single large pulse. It was observed that the single discharge system consistently produced castings with large amounts of trapped air.

To circumvent these problems a device capable of delivering a series of pulses was constructed. With this apparatus, it is possible to discharge in sequence four 9.6 KJ capacitor banks.

The discharge circuitry is shown in Figure 2. Each of the four capacitor banks are switched through a separate spark gap to the coil. The spark gap halves are positioned together for firing, and separated afterwards, mechanically. This insures that the capacitor banks discharge into the coil and not into one another. The sequence of discharges is initiated by a signal from a photo-cell, shown in Figure 1.

While the timing of the pulses is not as critical as with the old apparatus, it has been found experimentally that the first pulse should coincide with the impact of the slug with the mold.

If the first pulse occurs sooner there is excessive splattering. If it occurs later, filling will be less complete.

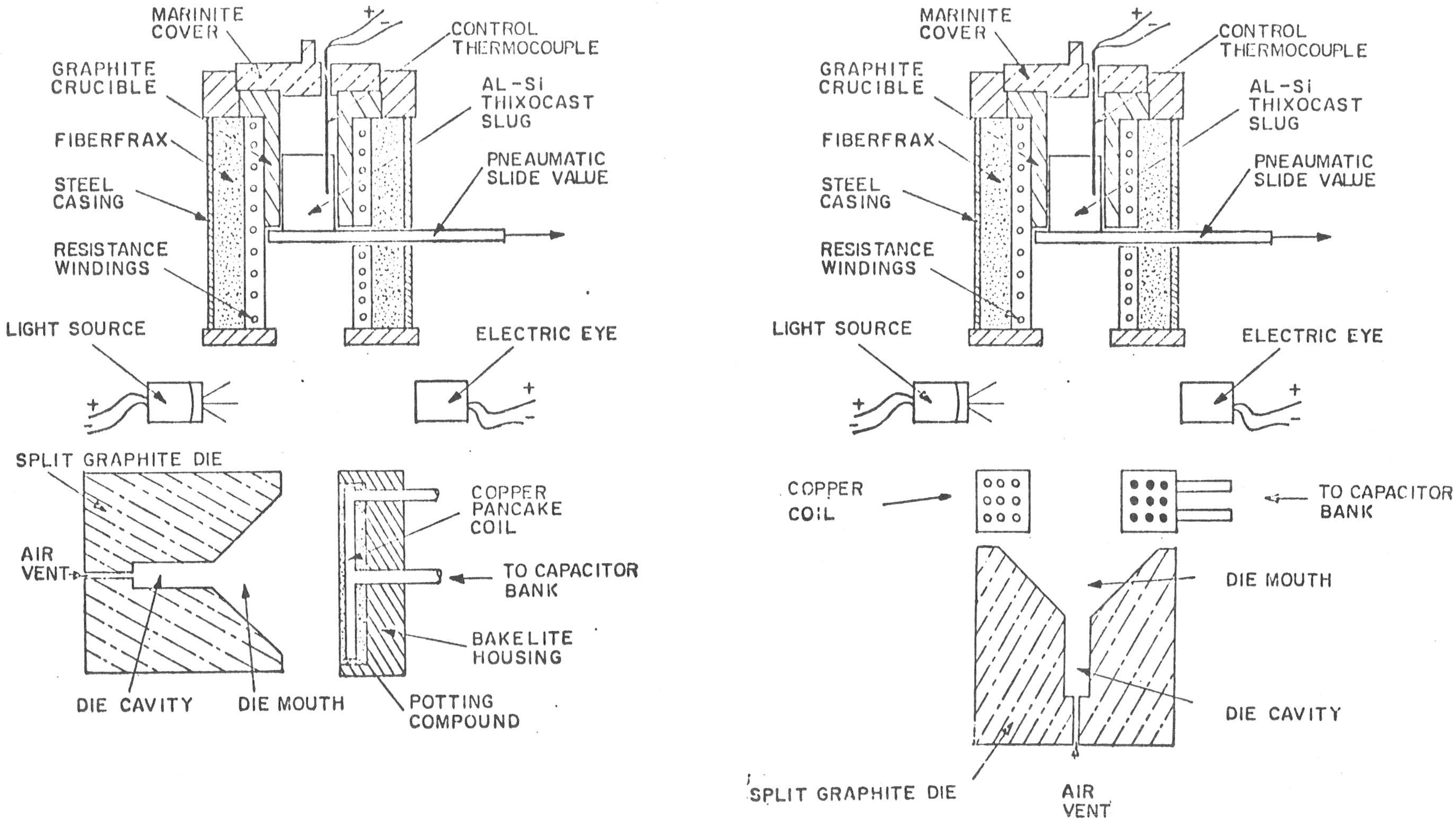
The equipment required to charge the capacitors was described in the previous report(1). Since that time, we have also added remote switching of the power supplies for safety reasons. The solenoid switches installed for this purpose are visible in Figure 2.

Results

An Al-5%Si casting produced by the electromagnetic injection technique is shown in Figure 3a. The electromagnetically injected castings exhibit much better conformity to the die cavity and an improved surface finish. Detracting from the casting quality, signs of air entrappment and incomplete filling are apparent in all castings. However, the castings show a significant improvement over those made with a single discharge. Figure 3b shows the microstructure of the casting at a location near the bottom of the down gate. Examination reveals that material in this region was initially semi-solid and thus no significant separation of solid and liquid occurs during mold filling. Major emphasis in the future will be toward the elimination of entrapped air and the production and examination of more complex castings.

References

1. M. C. Flemings et al., "Machine Casting of Ferrous Alloys", Interim Technical Report, ARPA Contract DAAG46-C-0110, 1 January - 30 December 1973, prepared for Army Materials and Mechanics Research Center, Watertown, Mass.



(a) (b)

Figure 1: Schematic diagram of electromagnetic casting machine; a) original arrangement, b) modified arrangement.

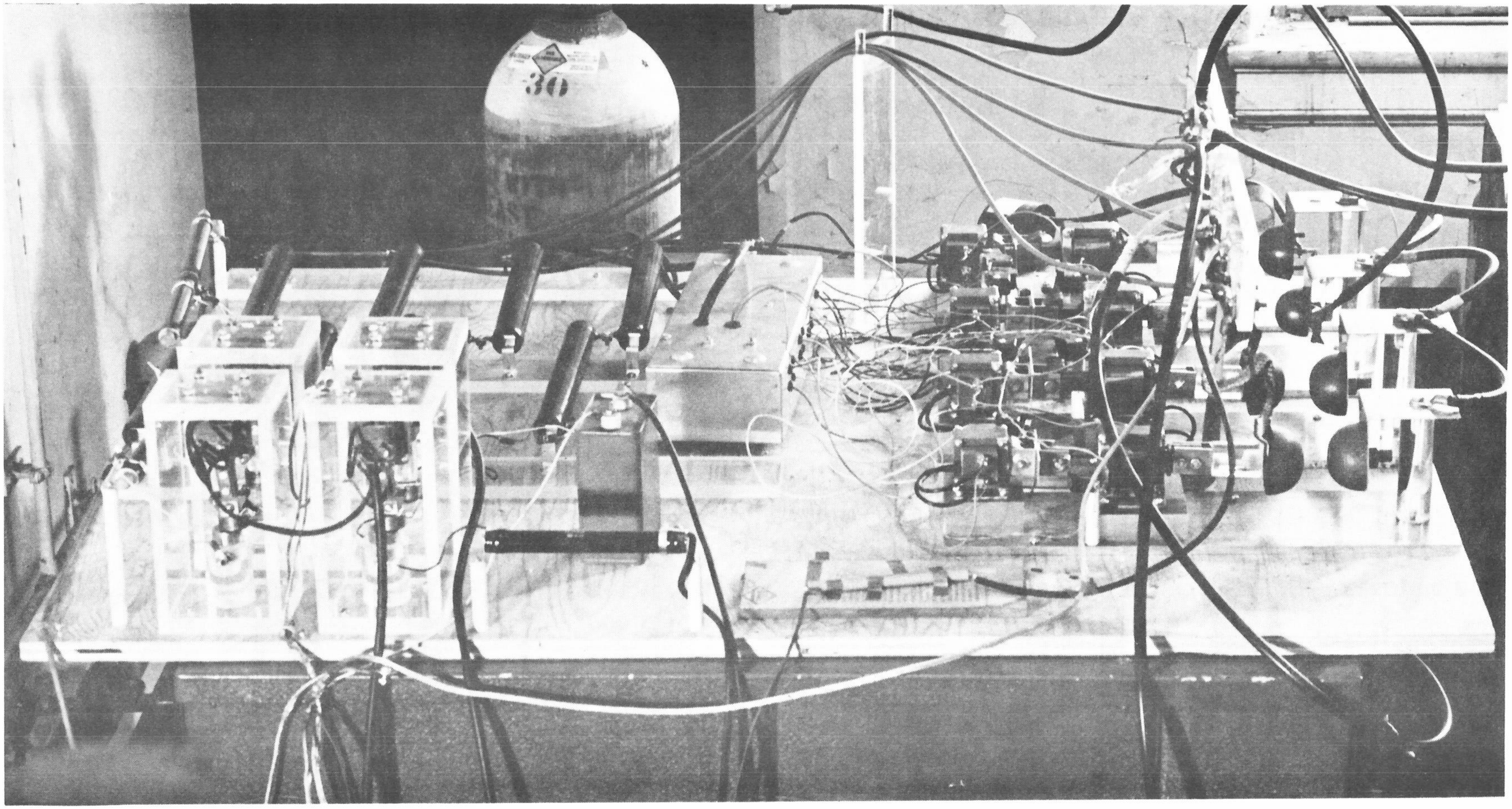
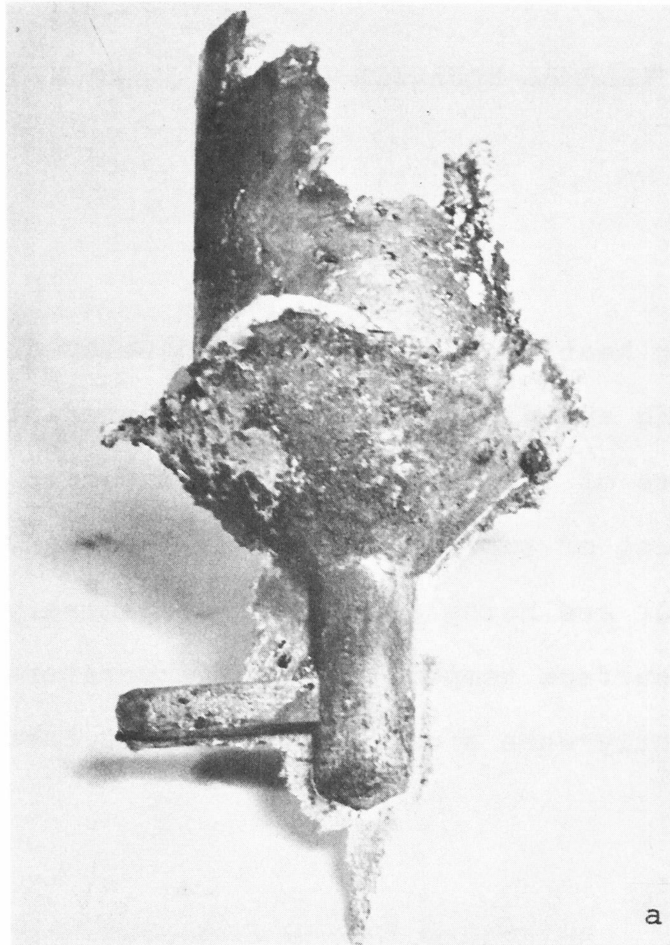


Figure 2: Photograph of spark-gap triggering mechanism.



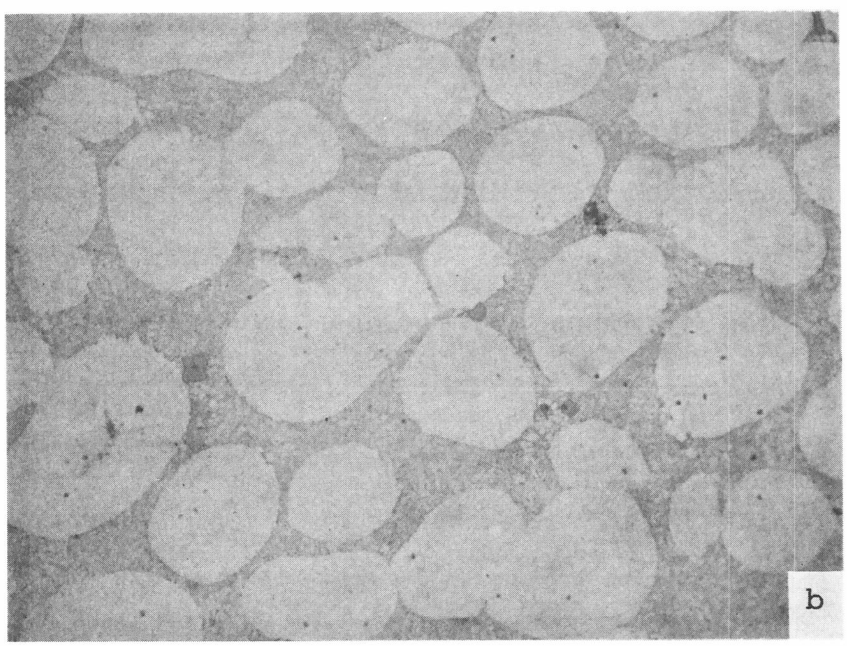


Figure 3: Electromagnetic casting made with multiple discharge; (a) photograph of unfinished casting, (b) photomicrograph showing structure near the bottom of the downgate, 50X.

CHAPTER 5. THERMAL BEHAVIOR OF DIES IN MACHINE CASTING

Summary

A computer heat flow analysis was developed to describe effects of casting and die conditions, and materials on die thermal behavior. Effects of fraction solid (for Rheocast and Thixocast metal) and effect of superheat (for fully liquid metal) on die thermal behavior are being examined. Preliminary results indicate that both die surface temperature and temperature gradient are lowered significantly when a cast iron alloy is cast in the semi-solid state.

Introduction

Die cracking, soldering, and surface wear are major problems confronted when attempts are made to die cast high temperature ferrous alloys. The characteristics of each phenomena are governed by the nature of heat flow within the die and the material properties of the die and the metal cast. Basically, the degree of die cracking depends upon the magnitude of the thermal gradient at the metal-die interface and the thermal fatigue characteristics of the die material. The extent of soldering and surface wear is determined by the die surface temperature (and subsequent surface hardness) coupled with the metal flow velocity within the die.

Previous attempts to improve die life have concentrated on the development of high temperature materials capable of withstanding severe thermal fatigue. Currently, work is underway at

M.I.T. to develop semi-solid ferrous alloy slurries whose reduced temperature and "effective" heat of fusion should have a dramatic effect upon die life. In an attempt to verify this expectation, a computer program has been written to assess the heat flow behavior as the melt superheat or fraction solid is varied. The material studied was cast iron (2.8 wt% C, 3.5 wt% Si). Calculations were carried out for a steel die. In the future, die temperature measurements will be conducted to corroborate the computer solution.

Computer Program

The computer program employs a one-dimensional heat flow model which is solved using a finite difference technique. Physical assumptions have been made to facilitate solution of the problem. They are:

(1) Physical properties of a phase are independent of temperature.

(2) The fraction solid of eutectic cast iron (2.8 wt%C, 3.5 wt%Si) is a linear function of temperature.

(3) Convection during injection is vigorous, yielding an essentially flat temperature distribution throughout the liquid during the casting of superheated liquid.

Solidification is accounted for by incorporating the heat

of fusion in an "effective" heat capacity C_{eff}:

$$C_{eff} = C_p + \left(\frac{\Delta H_f}{T_{LS}}\right) f_L \qquad T_{sol} < T < T_{liq}$$

where

C_p = heat capacity at constant pressure

ΔH_f = heat of fusion

f_L = fraction liquid

T_{LS} = temperature between liquidus and solidus temperatures

This procedure eliminates the need to directly consider the moving planar heat source produced by solidification. The differential equation to be solved is:

$$\alpha \frac{\partial^2 T}{\partial x^2} = \frac{\partial T}{\partial t} \tag{1}$$

The mold geometry investigated is shown in Figure 1. The boundary conditions and initial conditions are:

(1) $X = 0 \; ; \; \frac{\partial T}{\partial X} = 0 \; ,$ (symmetry)

(2) $X = L \; ; \; \frac{\partial T}{\partial X} = 0 \; ,$ (insulating)

(3) $X = D \; ; \; \frac{\dot{Q}}{A} = h \; \Delta T_s$

(4) $t = 0 \; , \; D < X < L \; ; \; T = T_D$

$$(5) \quad t = 0 \; , \quad 0 < X < D \; ; \quad T = T_o$$

where T_D and T_o are the initial die and melt temperatures, respectively, and ΔT_s is the temperature difference across the mold-metal interface caused by the surface heat transfer coefficient, h. The ratio $\dot{Q}/A$ represents the rate of heat flow through the mold metal interface per unit area, D is casting half thickness, and L is defined in Figure 1.

To solve equation (1) on the computer, a linear array of points is established within the die and die cavity, Figure 1. Subsequently, a heat balance is performed at each interior node and boundary conditions are applied at exterior points. Alternatively, equation (1) may be rewritten by substituting the appropriate first and second "differences" for the respective first and second partial differentials. This procedure yields the following difference equation for each interior node:

$$H_k\,(t + \Delta t) = H_k(t) + \left(\frac{k}{\rho\Delta}\right)\,[T_{k+1}\,(t) - 2T_k(t) + T_{k-1}(t)]\,\Delta t \qquad (2)$$

where

$$H_k(t) = \int_0^{T(t)} C_{eff}(T')\;dT'$$

and T_k represents the temperature at the k^{th} nodal point, Δ is the node spacing, Δt is the time interval between iterations, and ρ and k are the metal density and conductivity, respectively.

The sequence of steps executed by the computer program are as follows. First, the initial enthalpy and temperature at each node, as indicated by the initial conditions, are stored within the computer. For the first iteration, equation (2) or the appropriate boundary condition is applied successively at each node throughout the array, yielding $H_k(\Delta t)$. The associated temperature $T_k(\Delta t)$ is then calculated, and both the enthalpy and temperature arrays are stored for the next iteration. After the appropriate number of iterations the temperature distribution throughout the die and casting is printed. Successful operation of the computer program requires a suitable choice for the iteration interval, Δt. Excessively large values of Δt yield oscillation in the output. When present, trial and error selection of the interval size was used to eliminate the instability.

Results

A series of computer runs was made for a ¼" thick casting of eutectic cast iron (freezing range $1150^{\circ}C$ - $1190^{\circ}C$) cast in a steel die (initial temperatures - $0^{\circ}C$, $250^{\circ}C$, and $500^{\circ}C$). The initial melt temperature, T_o, was varied between runs to correspond to fraction solids in the range of $.1 < f_s < .5$ and superheats of $0^{\circ}C$, $50^{\circ}C$, $100^{\circ}C$, $200^{\circ}C$ and $250^{\circ}C$. Also various values of the surface heat transfer coefficient, h, were employed.

Figures 2 and 3 show the mold surface temperature, T_s, as a function of time for a casting made from superheated liquid and a casting made with semi solid cast iron (fraction solid = .5). Figure 2 represents the results for h = 10 cal/$^{\circ}C$ sec cm^2 (small

interface resistance). Figure 3 shows the results for h = .5 cal/ ^{o}C sec cm^{2} (moderate interface resistance). In both figures, the mold surface temperature is much higher for castings produced with superheated liquid. From Figure 2 the maximum difference in die surface temperatures is 480^{o}C for h = 10 (cgs).

As discussed previously, the temperature gradient in the die at the die metal interface is also an important parameter affecting die life. In Figure 4, the surface gradient $(\frac{dT}{dx})_{SURFACE}$ is plotted versus time for h = 10 (cgs). The initial melt temperatures are 1170^{o}C (f_s = .5) and 1440^{o}C (250^{o}C superheat), respectively. Again, the difference in behavior is drastic. The molten alloy with a 250^{o}C superheat yields a die surface temperature gradient nearly twice as large as the semi-solid (f_s = .5) cast iron.

Conclusions

1) A computer program was written and executed to provide a comparison between the die thermal history for castings produced with completely liquid, superheated, cast iron and for semi-solid cast iron.

2) Preliminary results of the computer program indicate that a significant lowering of both die surface temperature and surface temperature gradient is achieved by casting the metal in the semi-solid state. Experiments are currently underway to verify these findings.

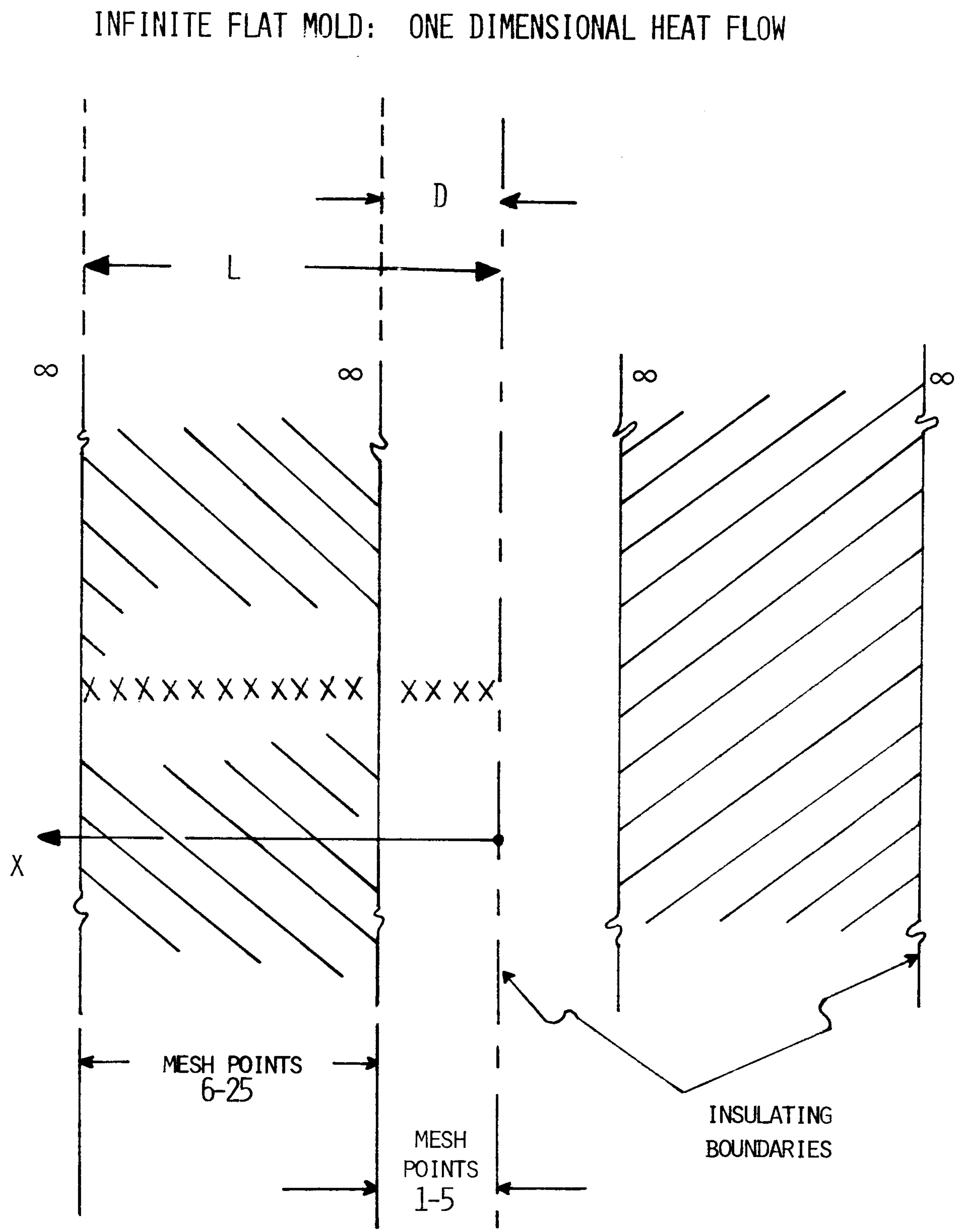


Figure 1: Schematic diagram of one dimensional computer model.

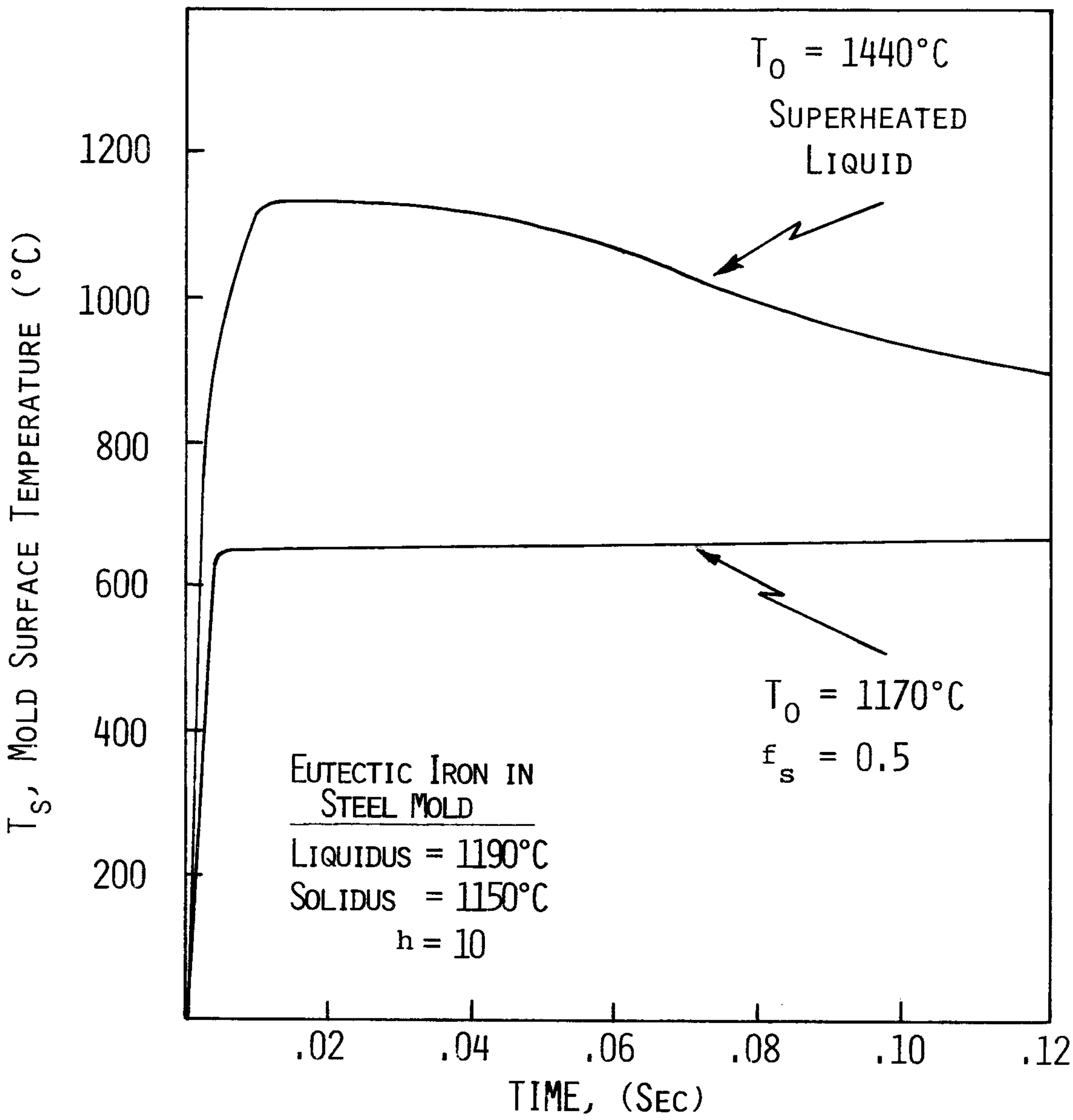


Figure 2: Graph of die surface temperature versus time; initial melt temperature, T_o, heat transfer coefficient, h = 10 cal/°C sec cm^2. Metal cast from the fully liquid (superheated) state, T_o = 1440°C, and from semi-solid (f_s = 0.5) state, T_o = 1170°C.

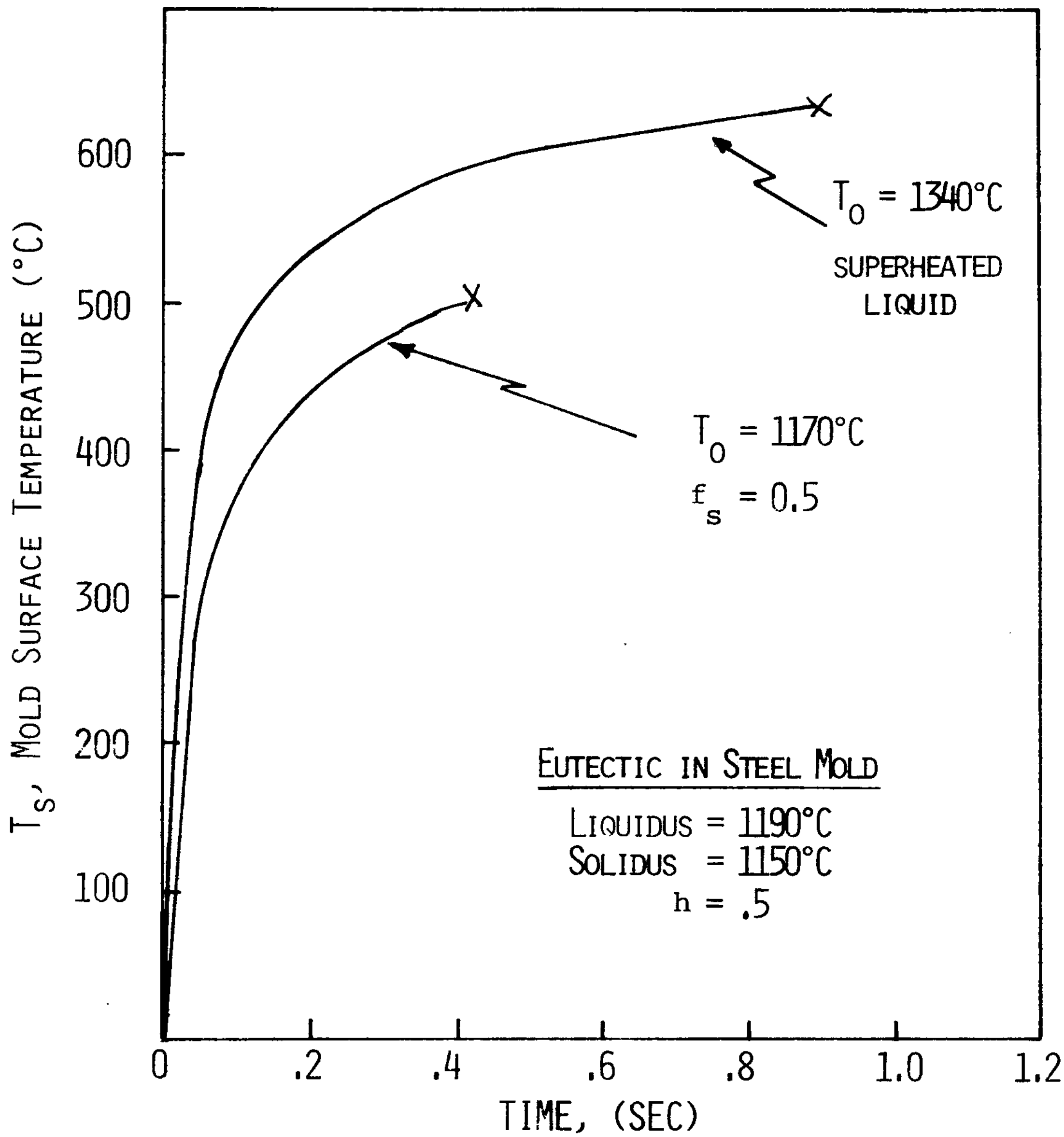


Figure 3: Graph of die surface temperature versus time; initial melt temperature, T_o, heat transfer coefficient, h = 0.5 cal/°C sec cm^2. Metal cast from the fully liquid (superheated) state, T_o = 1340°C, and from semi-solid (f_s = 0.5) state, T_o = 1170°C.

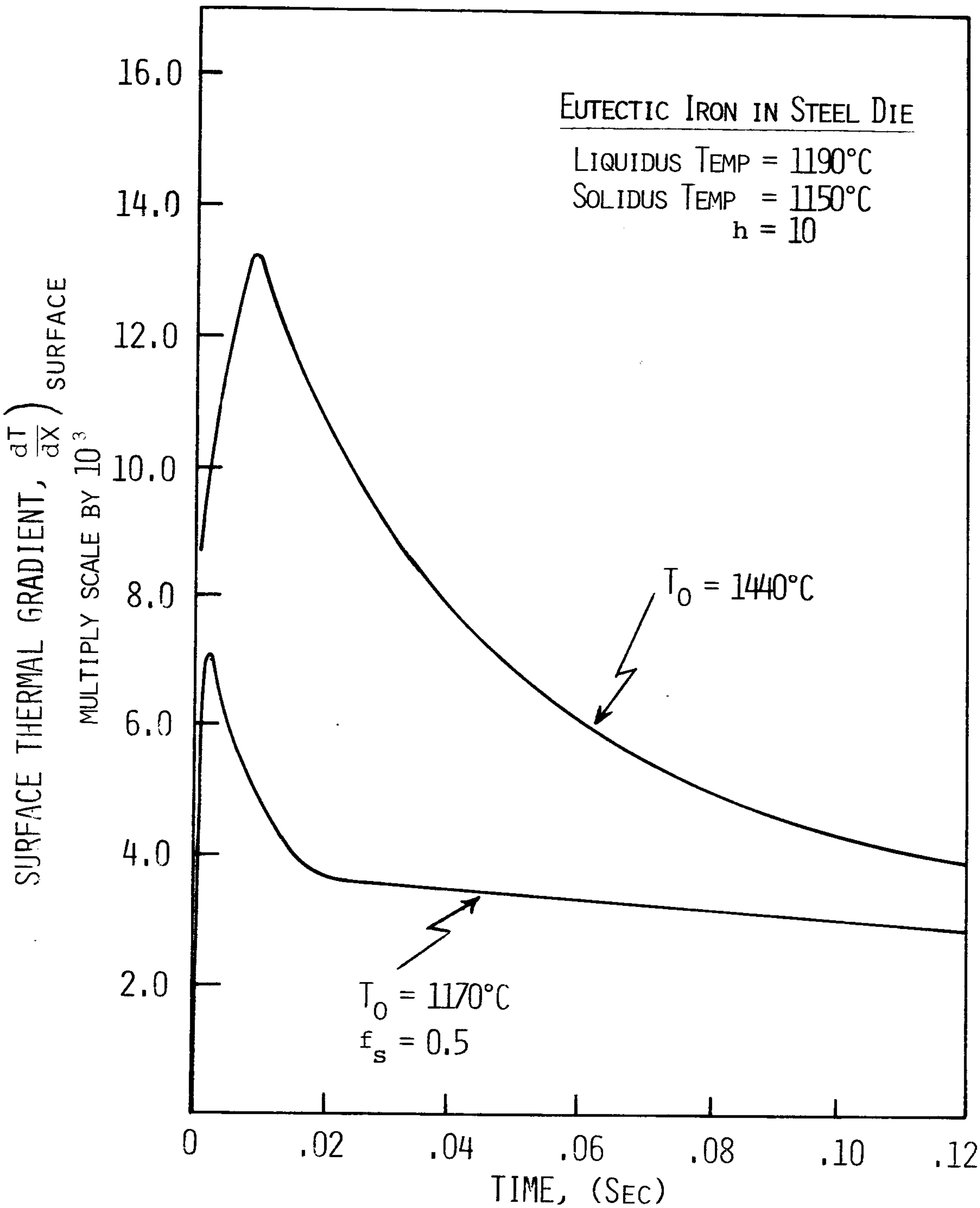


Figure 4 : Graph of surface thermal gradient versus time; initial melt temperature, T_O, heat transfer coefficient, h = 10 cal/°C sec cm^2. Metal cast from the fully liquid (superheated) state, T_O = 1440°C, and from semi-solid (f_s = 0.5) state, T_O = 1170°C.

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This report describes research conducted at Massachusetts Institute of Technology during the first half of the second year of a joint university-industry research program on casting of ferrous alloys. Work during this period continued on both low temperature "model" systems, and on a ferrous alloy. Emphasis was on casting of semi-solid alloys, especially semi-solid alloys produced in a continuous slurry producer.

A low temperature casting system described earlier was improved. This

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system consists of a continuous semi-solid slurry producer, "gel" chamber, and casting machine. The system was used to produce about one hundred castings of Sn-15%Pb alloy. High speed motion pictures taken through a transparent die show that the semi-solid slurry flows into the die more smoothly than fully liquid metal, entrapping less gas. Radiography and metallography show the semi-solid castings are freer of entrapped gas and shrinkage than are castings made similarly of fully liquid metal.

Construction and testing of a casting system for high temperature alloys was completed. The system comprises a continuous slurry producer described earlier, a "gel" chamber, and a "low pressure" die casting machine. The completed casting system was tested using copper base 905 alloy (88wt%Cu, 10wt%Sn, 2wt%Zn) as a model high temperature alloy system. Radiographic analysis of 51 castings made show that overall casting quality improves with increasing fraction solid in the slurry.

Modifications of the high temperature casting system described above were made to permit casting ferrous alloys. Successful preliminary experiments were carried out with a hypoeutectic Fe-2.5%C-3.1%Si cast iron alloy.

Work was continued to develop design parameters for an electromagnetic piston for rapid mold injection of semi-solid metals. The electromagnetic casting machine described earlier was modified. Modifications include an improved coil-die arrangement and development of a multiple discharge triggering system. Castings produced with a semi-solid aluminum alloy using the modified machine show improved die filling and reduced air entrapment.

A computer heat flow analysis was developed to describe effects of casting and die conditions, and materials on die thermal behavior. Effects of fraction solid (for Rheocast and Thixocast metal) and effect of superheat (for fully liquid metal) on die thermal behavior were examined. Preliminary results indicate that both die surface temperature and temperature gradient are lowered significantly when a cast iron alloy is cast in the semi-solid state.